Nanosecond laser-induced breakdown in pure and Yb^{3+} doped fused silica

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MOTIVATION

- Our program goal is to maximize the pulse energy from large mode area fiber amplifiers at 1.064 μm.
- Optical damage is the ultimate limit to amplified pulse energy from a fiber.
- The literature on nanosecond damage of fused silica is too confusing to use as basis for fiber amplifier design. We need better measurements and understanding. We also need to measure the damage threshold of Yb^{3+} - doped fused silica.
  - Reported values of damage threshold irradiance/fluence vary over orders of magnitude
    a. I_{th} = 605 GW/cm^2, t_0=31 ns, w_0=6.15 μm
    b. I_{th} = 22 ± 5 GW/cm^2, t_0=7 ns, w_0=6 μm
  - Is the damage determined by Irradiance or Fluence?

a) M. Soileau and M. Bass, IEEE JQE Qe-16, 814 (1980).
b) L. Gallais *et al*., Optics Express 10, 1465 (2002).

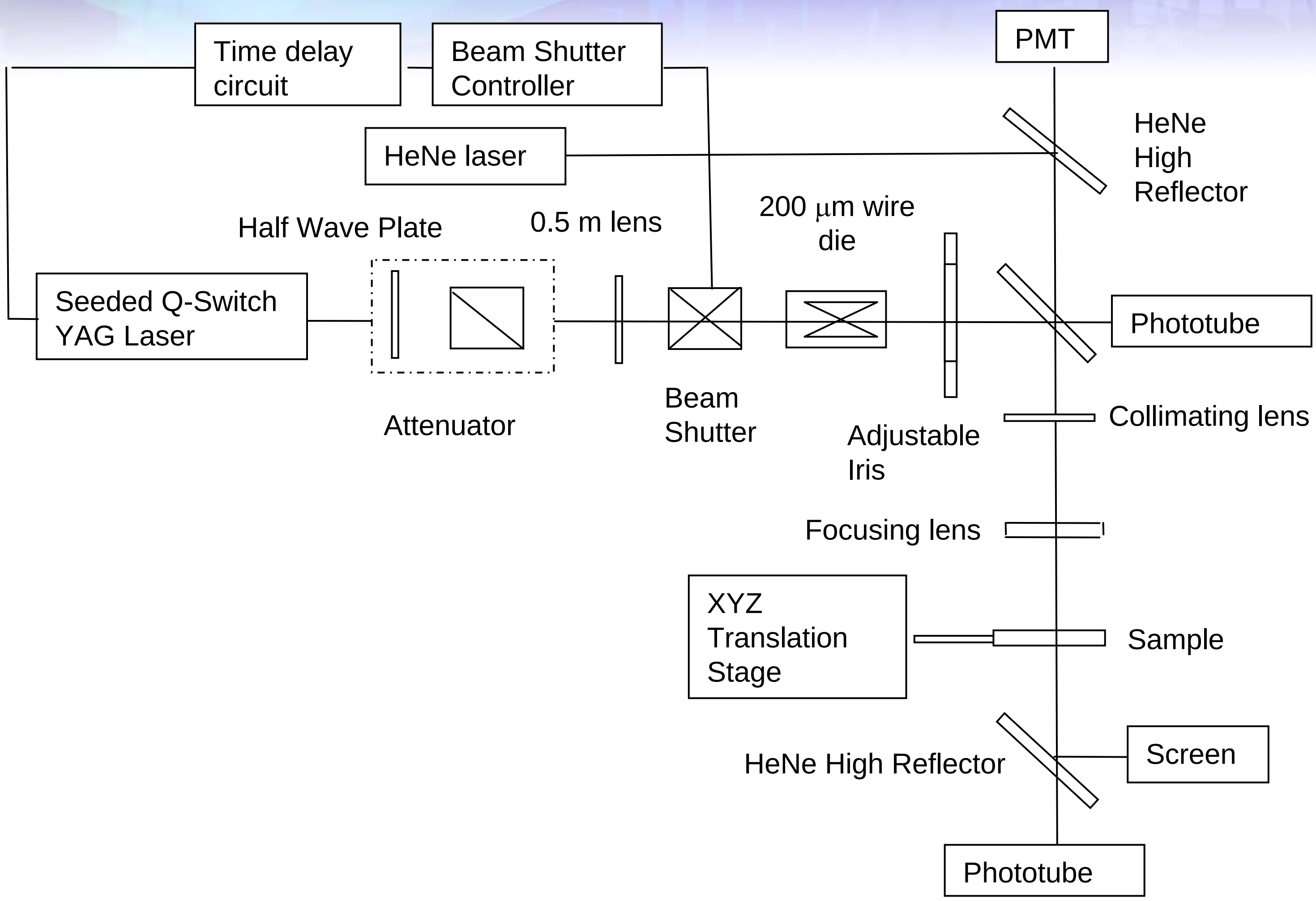
ISSUES

1. Detection of optical breakdown
2. Time and spatial profiles of laser pulses
3. Location and the size of the laser focus
4. Self focusing
5. Stimulated Brillouin Scattering (SBS)
6. Bulk optical breakdown damage threshold
7. Damage mechanism and morphology
8. Focal size effect
9. Influence of Yb^{3+} doping

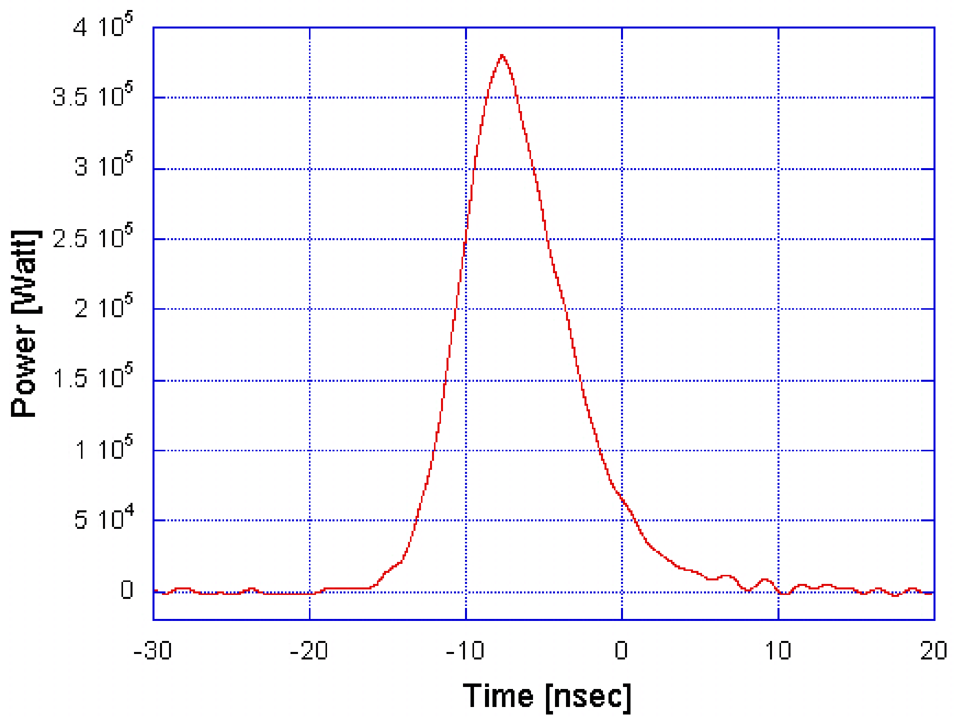
1. DETECTION OF OPTICAL BREAKDOWN

- Laser induced optical damage is always accompanied by plasma formation at the focal spot.
- We detect the white light emitted by this plasma as the primary indicator of optical damage.
- We monitor incident and transmitted light pulses with fast photo detectors.
- We monitor transmission of a HeNe probe beam which propagates collinearly with the pump beam.

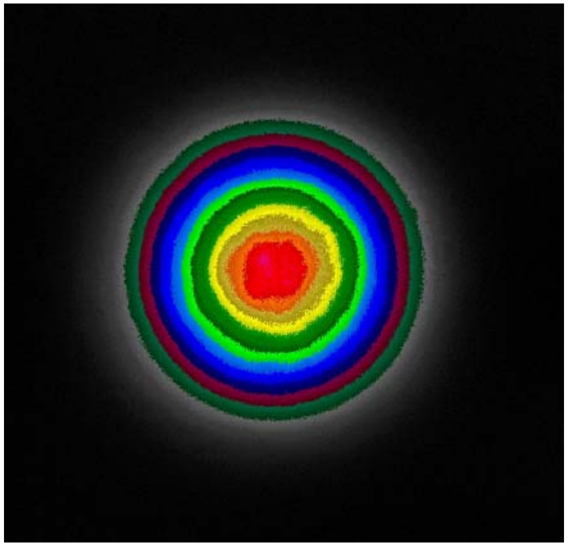
1. DETECTION OF OPTICAL BREAKDOWN



2. TIME AND SPATIAL PROFILES OF LASER PULSES



Temporal profile, t_0(FWHM)= 7.5 nsec.

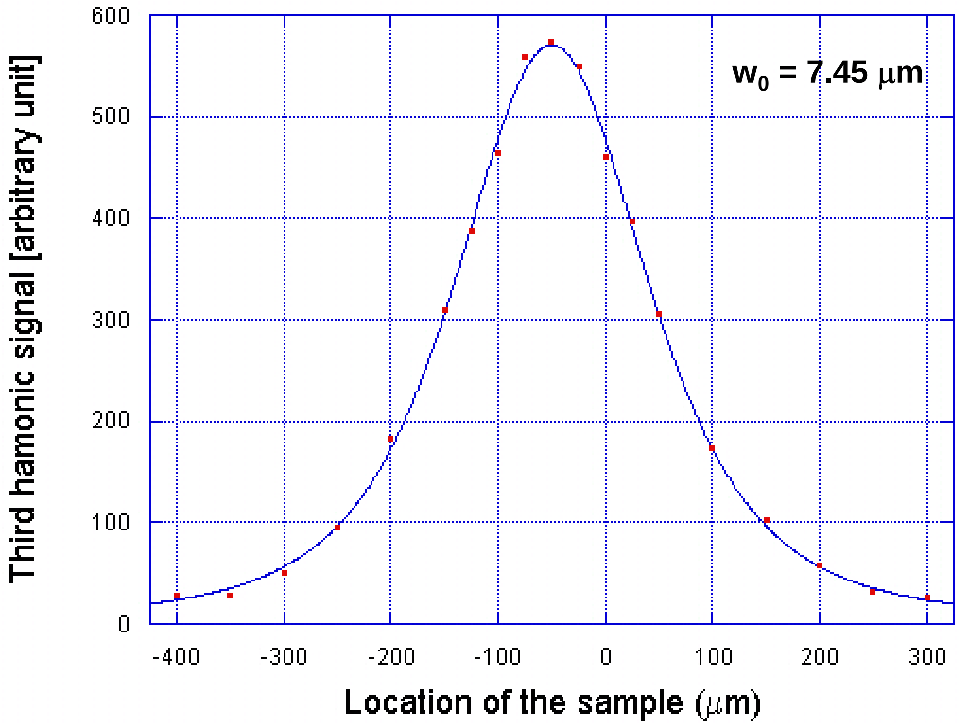


Spatial profile

3. LOCATION AND SIZE OF THE LASER FOCUS

Locating the focal waist relative to the sample input face.

Measuring the focusing spot size.

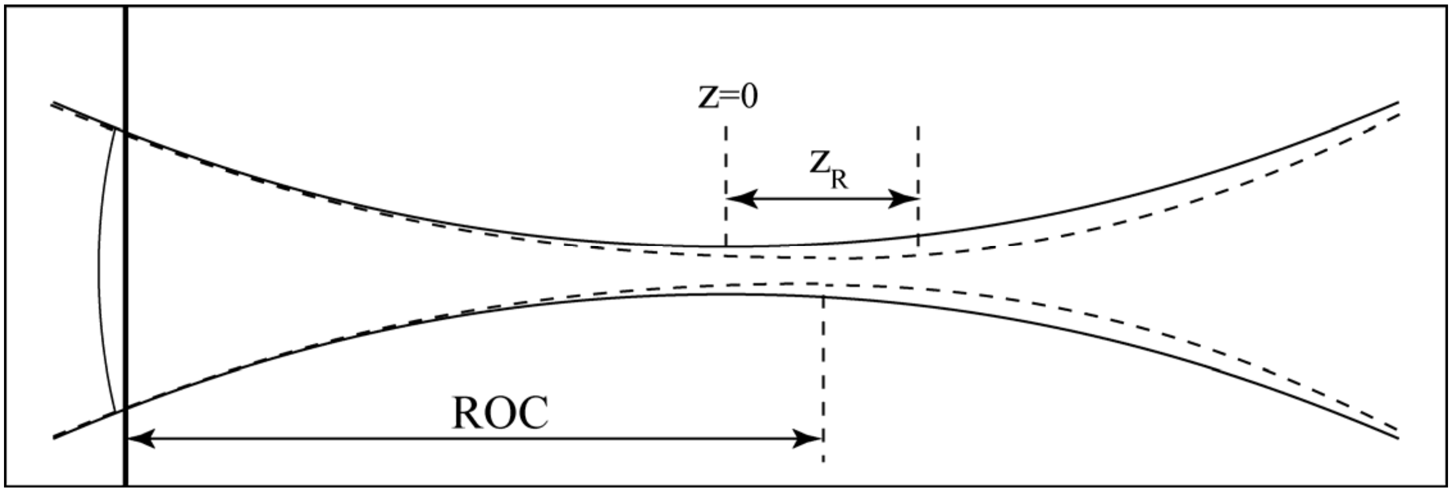


Surface third harmonic signal as a function of the front surface location.

$$Sig_{THG} = \frac{C}{\left(z_R^2 + [z - z_o]^2\right)^2}$$

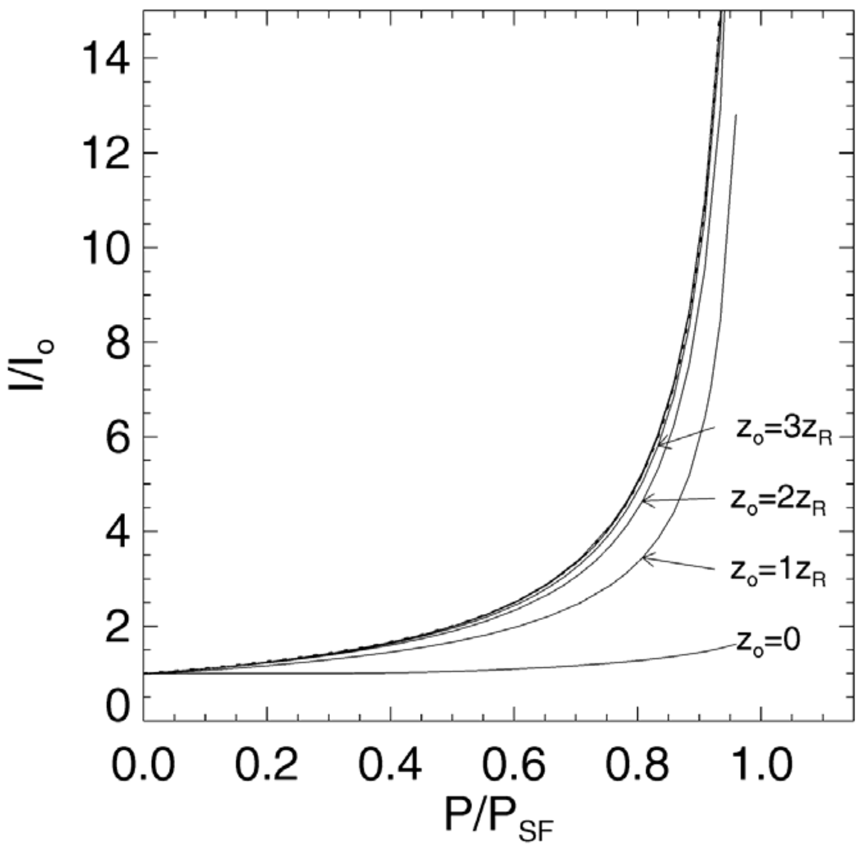
4. SELF FOCUSING

$$n = n_0 + n_2 I$$



Self focusing moves the focus downstream and increases the maximum irradiance

4. SELF FOCUSING



Irradiance enhancement for different depths of focus.

$$n = n_0 + n_2 I$$

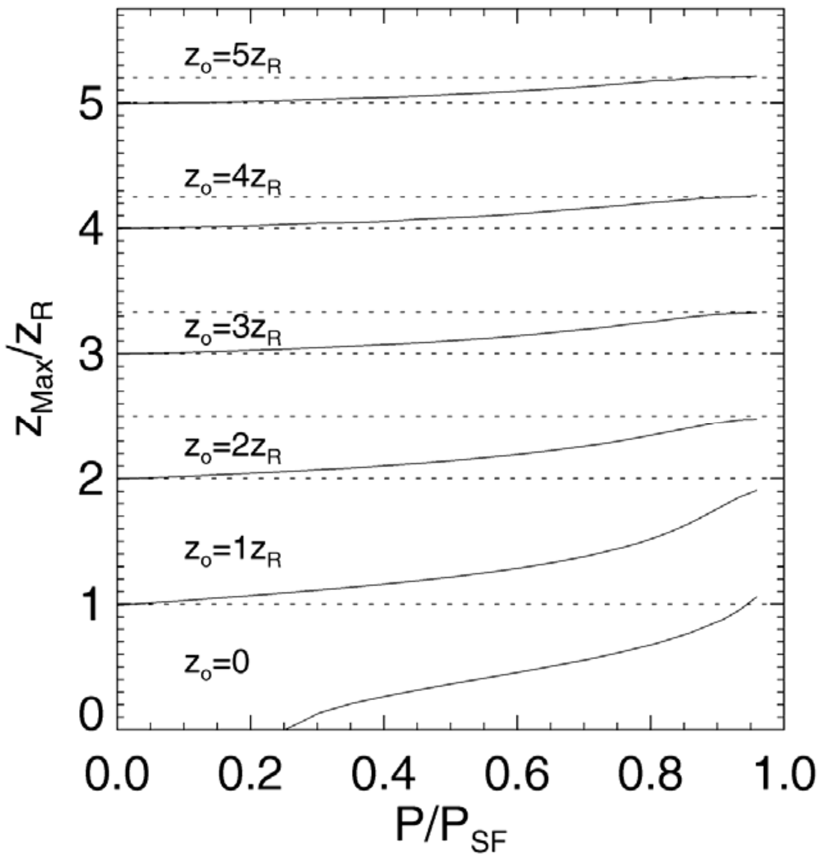
$$I_{corr} = \frac{I}{1 - P/P_{sf}}$$

$$P_{sf} = \frac{3.73\,\lambda^2}{8\,\pi\,n\,n_2}$$

P_{sf}(lin) = 4.29 MW

P_{sf}(cir) = 5.89 MW

4. SELF FOCUSING



- The maximum focal shift is z_R^2 / z_0

5. STIMULATED BRILLOUIN SCATTERING

SBS threshold estimate for a focused Gaussian beam:

$Gain_{SBS} = g_0\ I_0\ z_R$

$= g_0\ (2\ P\ /\ \pi\ w_0^2)\ (\pi\ w_0^2\ /\ \lambda)$

$= 2\ g_0\ P\ /\ \lambda$

Gain = 30 at threshold

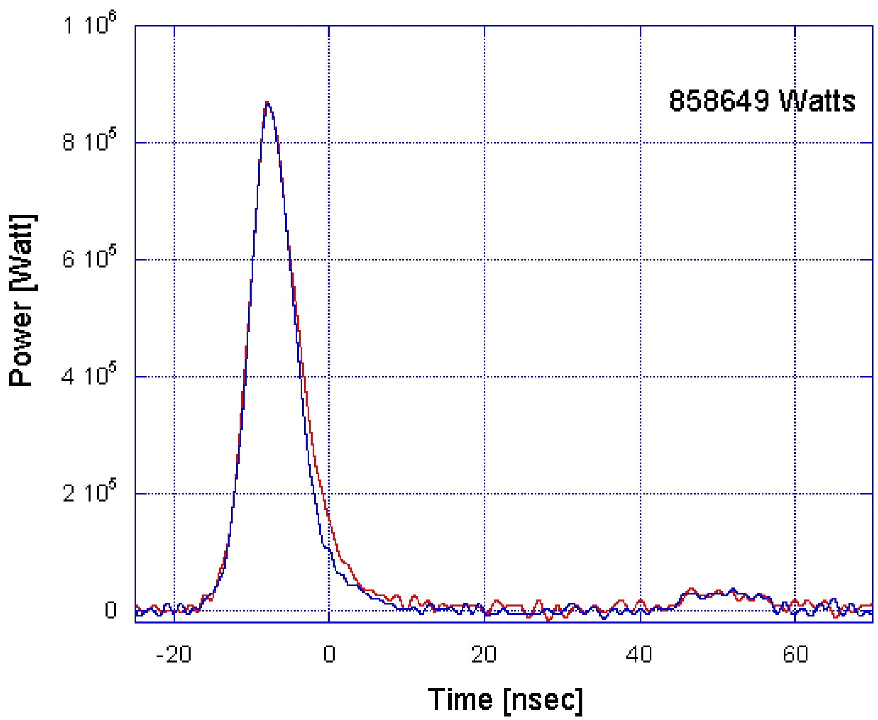
P_{thresh} = 0.3 MW for cw light

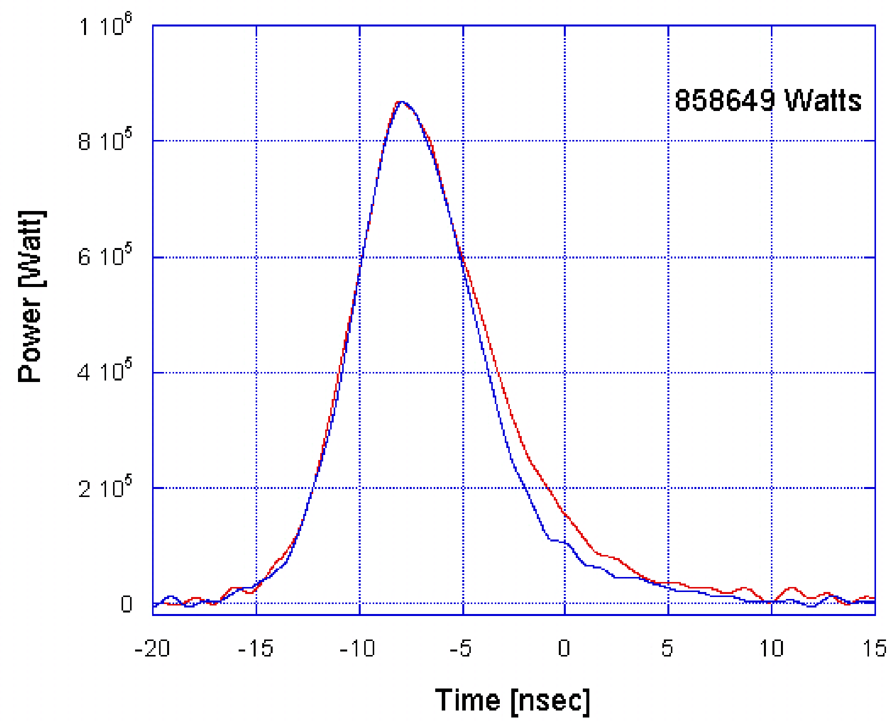
t_{SBS} = 30 ns

P_{thresh} = 0.9 MW for a 10 ns pulse

5. STIMULATED BRILLOUIN SCATTERING

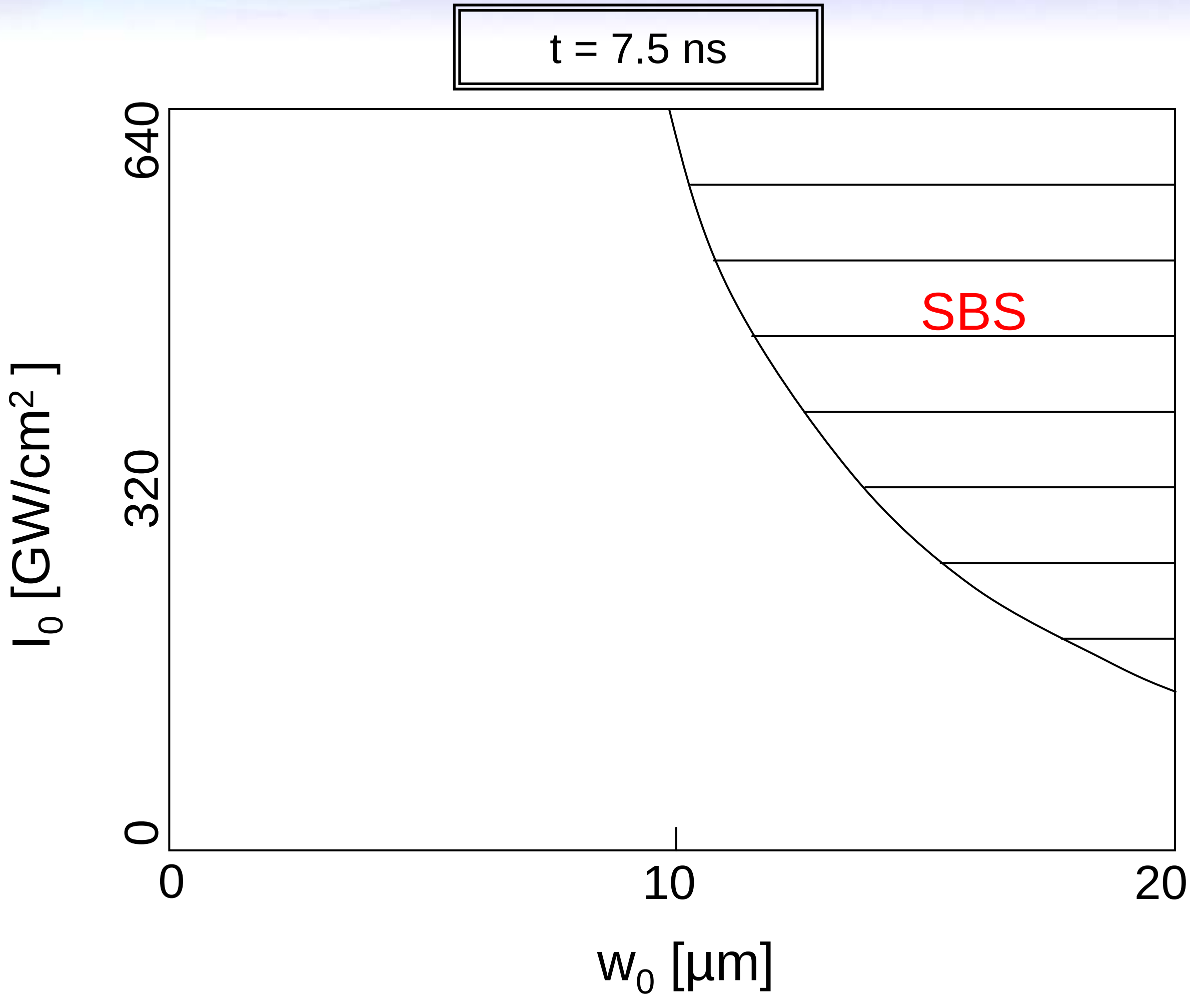
Incident (red) and transmitted (blue) waveforms of linearly polarized light at the power slightly above the SBS threshold.



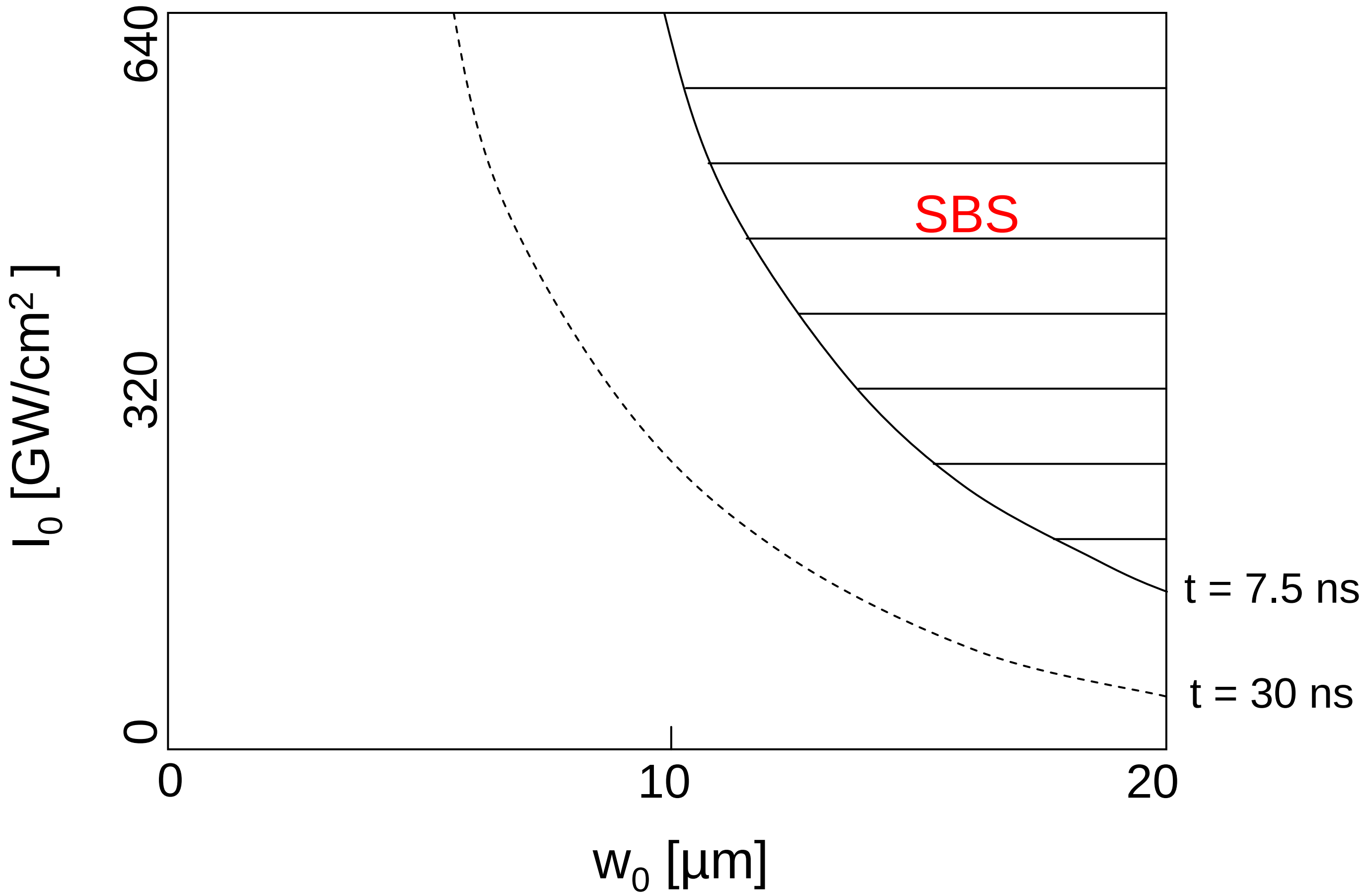


D1 fused silica, w_0 = 17 μm, t_0 (FWHM) = 7.5 ns, the measured SBS threshold in fused silica is 0.86 MW.

5. STIMULATED BRILLOUIN SCATTERING



5. STIMULATED BRILLOUIN SCATTERING

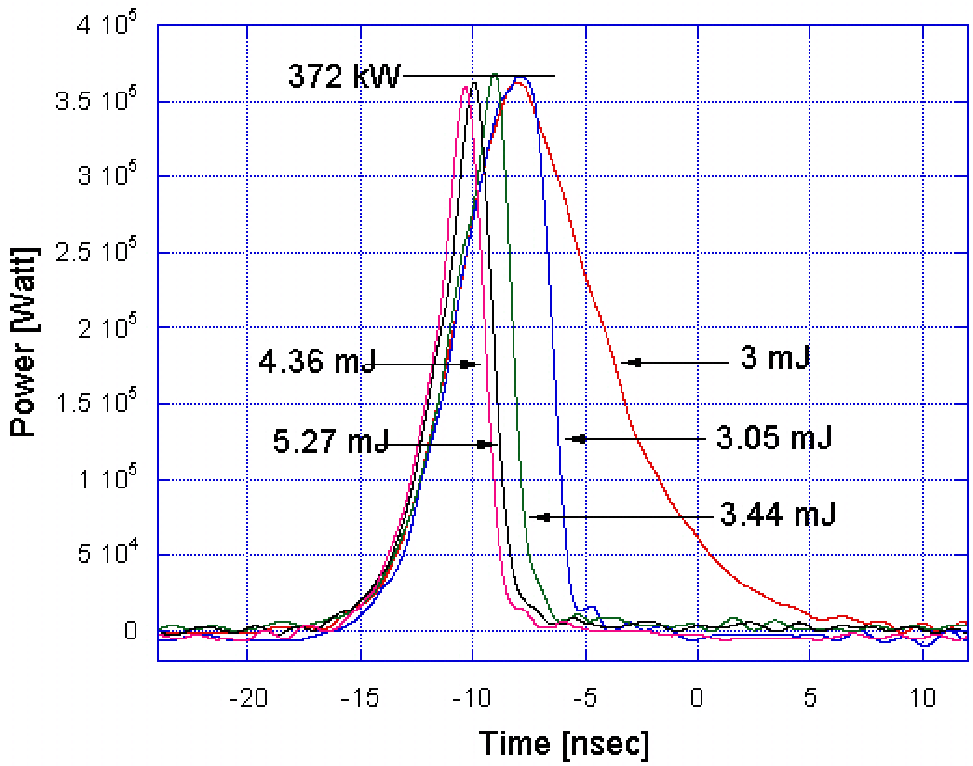


6. BULK OPTICAL BREAKDOWN

D1 fused silica, w_0 = 7.45 μm, t_0 (FWHM) = 7.5 ns

Linear polarization: P = 374.2 ± 4.0 kW, I_{corr} = 470.7 ± 5.0 GW/cm^2

Circular polarization: P = 387.7 ± 6.2 kW, I_{corr} = 476.4 ± 7.6 GW/cm^2

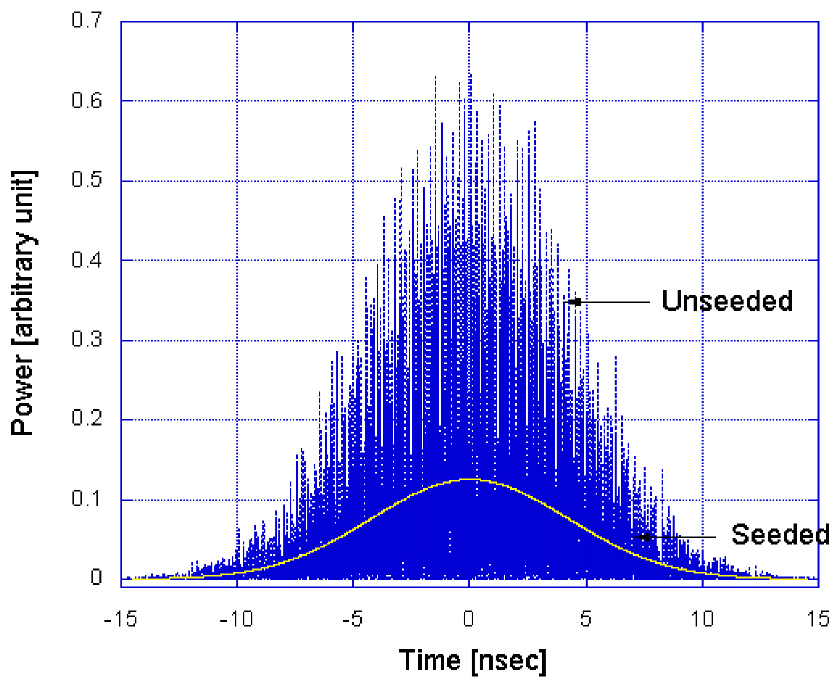


Transmitted power profiles with and without optical breakdown, w_0 = 7.45 μm, t_0 (FWHM) = 7.5 ns

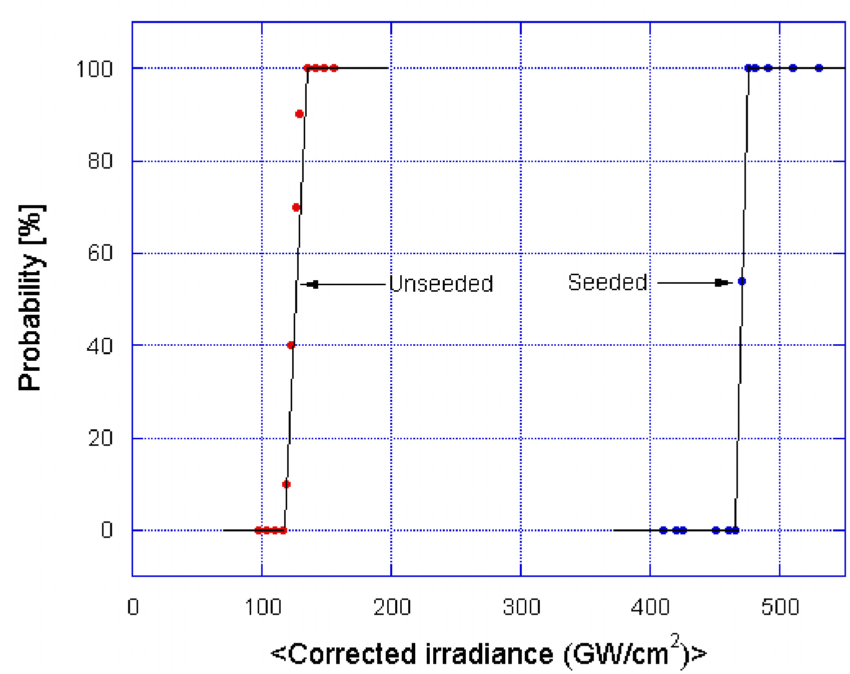
For w_o = 7.45 μm breakdown is nearly instantaneous at 0.372 MW - well below the SBS threshold of 0.85 MW.

Damage thresholds for A0, B0, B1, D0, D1, D3, D5 Corning fused silica are identical within our 1% measurement uncertainty.

6. BULK OPTICAL BREAKDOWN



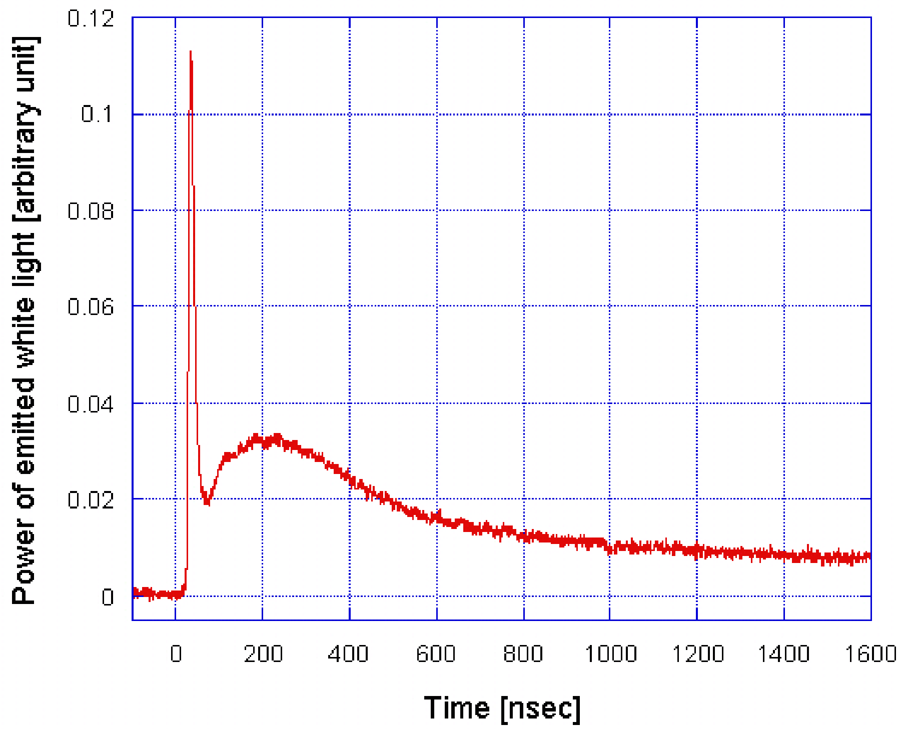
Temporal profiles of a seeded and an unseeded laser of the same pulse energy (8 longitudinal modes).



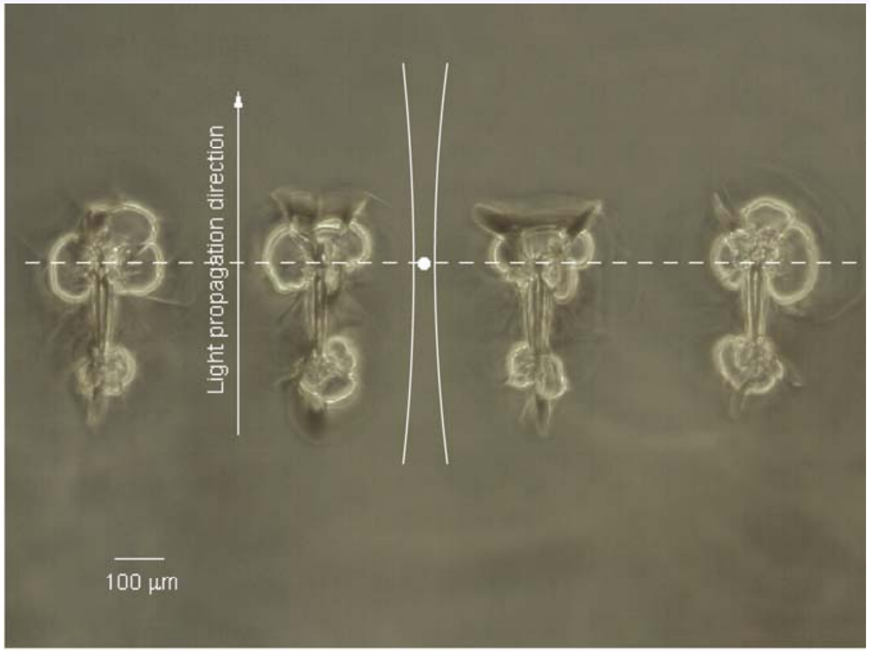
Statistical and deterministic behaviors of optical breakdowns induced by an unseeded laser and a seeded laser, respectively.

This strongly suggests that laser irradiance is the deciding factor for optical breakdown and the damage occurs on 10 ps time scale or shorter.

7. DAMAGE MECHANISM AND MORPHOLOGY



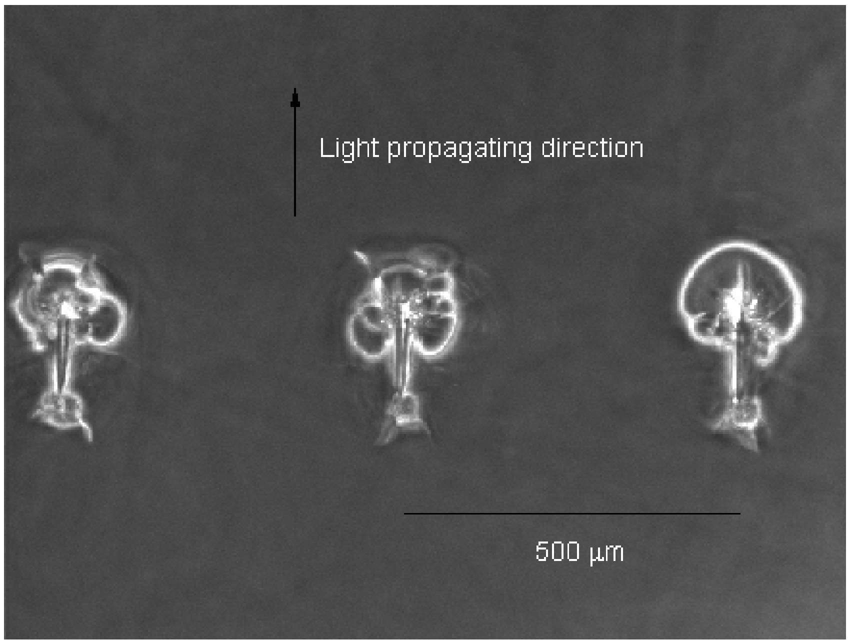
White light emission from optical breakdown
w_0 = 7.45 μm , t_0 (FWHM) = 7.5 ns



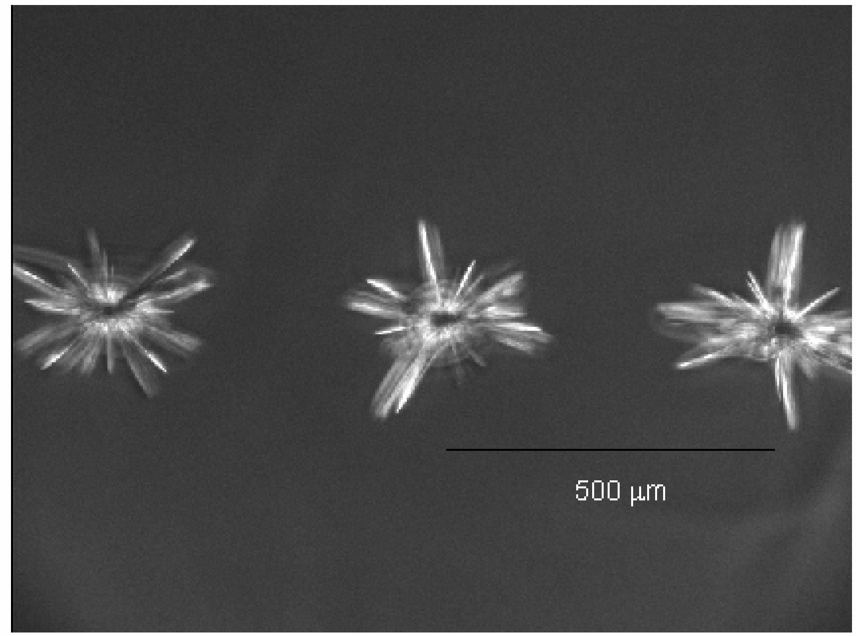
Optical damage near damage threshold
w_0 = 7.45 mm, t_0 (FWHM) = 7.5 ns

Damage is always upstream from the focus

7. DAMAGE MECHANISM AND MORPHOLOGY



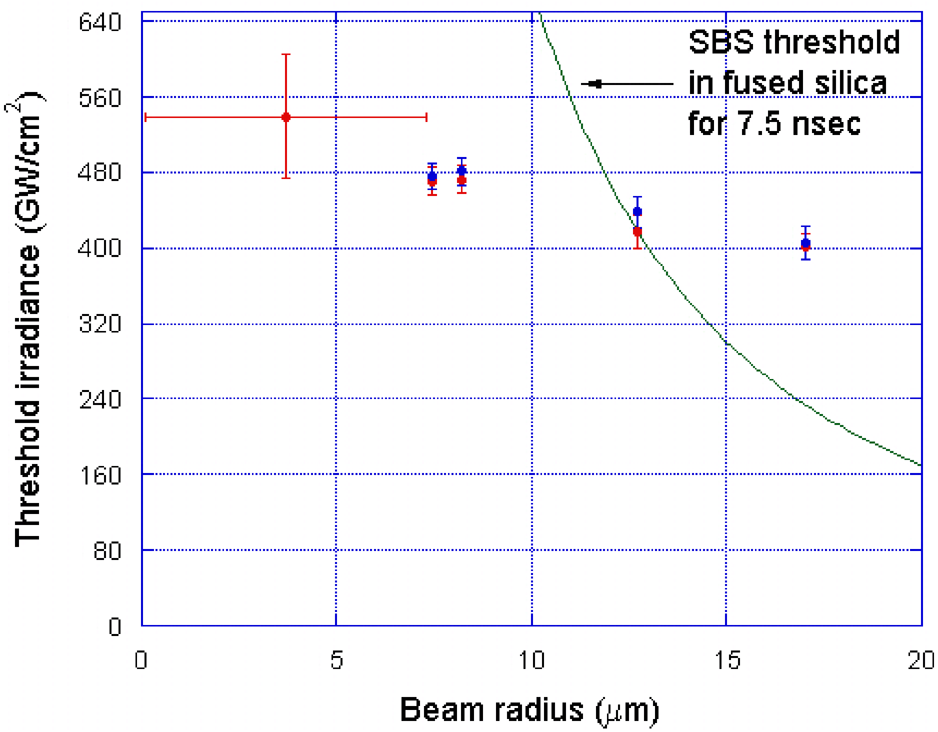
Side view



Top view

8. FOCAL SIZE EFFECT?

Damage threshold irradiance as a function of beam radius.



SBS threshold is slightly smaller than the damage thresholds for w_0 = 12.7 μm, and t_0 = 7.5 ns

For $w_0 \geq$ 12.7 μm, the damage threshold is reduced by the SBS.

Leftmost datum is for retro-reflected beam.

There is no apparent focal size effect on the damage irradiance.

9. INFLUENCE OF 1% Yb^{3+} DOPING

- $w_0 = 8.1\ \mu m$, $t_0 = 8.35$ nsec, linearly polarized light (no SBS)

- Two methods:
  1. Multiple laser pulses on each spot, energy step = 0.050 mJ.
  2. Single pulse on each spot, breakdown threshold deduced from shape of transmitted pulse.

- These two methods give <3% difference in $I_{corr\text{-}lin} = 640 \pm 19\ GW/cm^2$.

- Scatter in preform cores increases uncertainty of damage threshold somewhat

Damage threshold for 1% Yb3+-doped silica is 35% higher than for pure silica.

CONCLUSIONS

- The damage irradiance in fused silica is I_{lin} = 471 ± 5.0 GW/cm^2 and I_{cir} = 476 ± 7.6 GW/cm^2 for t=7.5 ns, w_0 = 7.45 µm.
- SBS threshold power in fused silica is P_{lin} = 851.0 ± 2.9 kW and P_{cir} = 852.0 ± 2.3 KW for t = 7.5 ns.
- The damage irradiance in 1% Yb^{3+} doped fiber preform is I_{lin} = 640 ± 19 GW/cm^2 for t=8.35 ns, w_0 = 8.1 µm.
- Damage by ns pulses occurs at a precise threshold irradiance, not a threshold fluence.
- The damage threshold irradiance is reduced by SBS.
- There is no evident focal size effect.
- Self focus corrections are necessary in deducing the true damage irradiance.
- Damage occurs on ≤10 ps time scale.

BULK OPTICAL BREAKDOWN WITH SBS

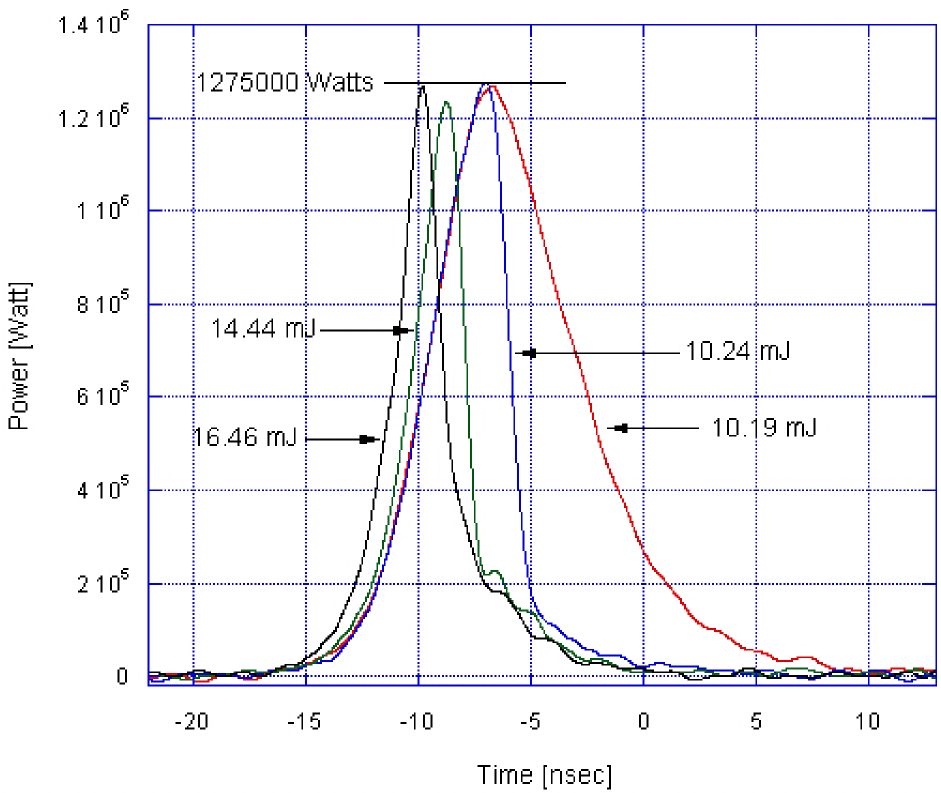


Figure 14: Transmitted waveforms through fused silica sample with and without optical breakdown, w_0 = 17 μm, t_0 (FWHM) = 7.5 nsec

For the 17 µm spot size at the focus of the 2-inch focal length lens, the breakdown is nearly instantaneous once the irradiance reaches the threshold breakdown value. A drop in the breakdown irradiance at 14.44 mJ pump energy possibly shows an enhancement of SBS.

BULK OPTICAL BREAKDOWN WITH SBS

The white light emitted by the optical breakdown for linearly polarized light shows the trace of the amplified SBS pulse absorbed by the plasma.

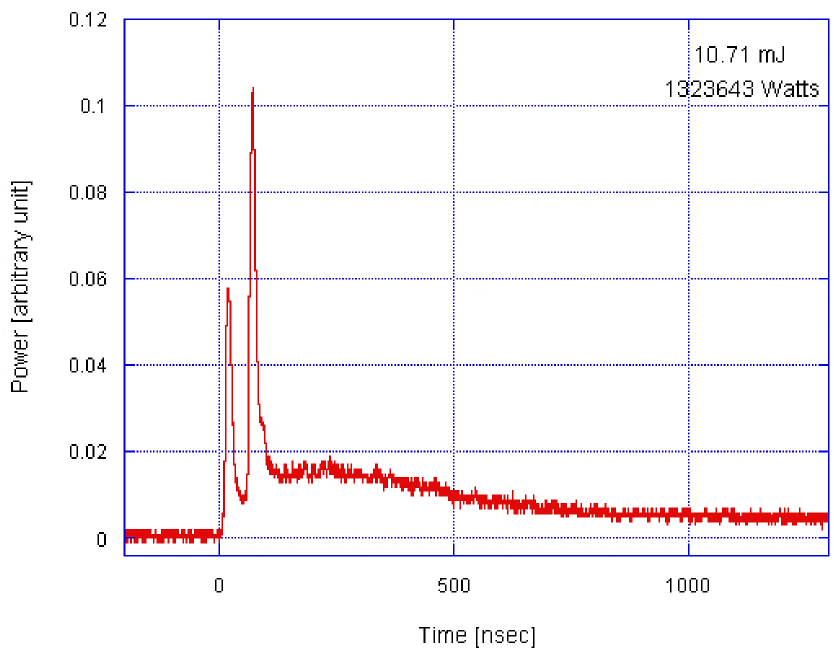


Figure 15: SBS assisted white light emission from optical breakdown in fused silica, linear polarization.

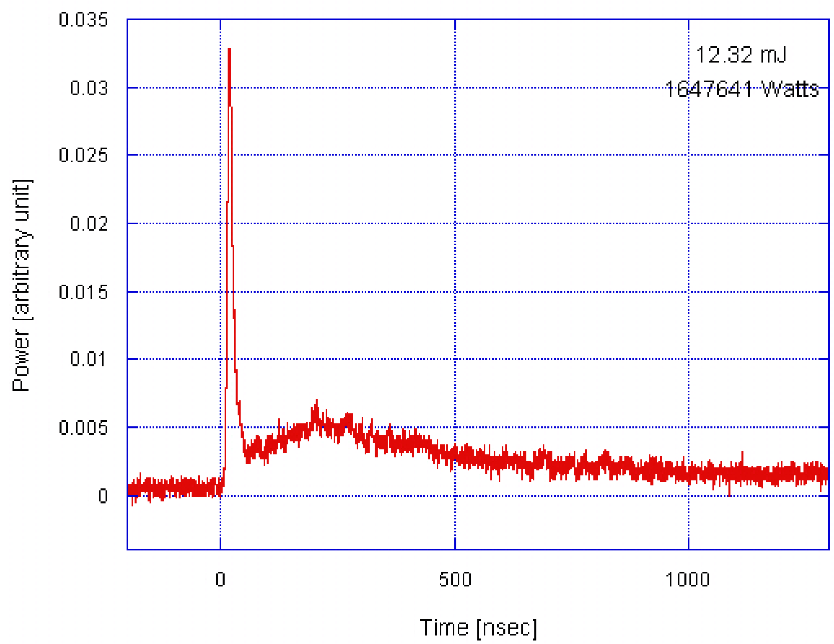
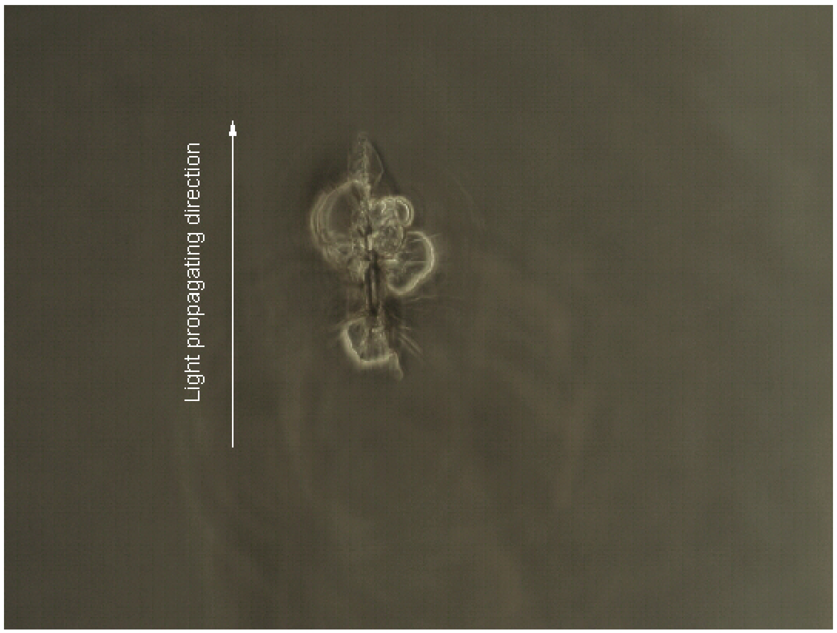


Figure 16: SBS assisted white light emission from optical breakdown in fused silica, circular polarization.

BULK OPTICAL BREAKDOWN WITH SBS



(a)

(b)

Figure 17a, b: Optical damage generated by circularly polarized light at 11.53 mJ (a) and by linearly polarized light at 10.71 mJ (b). The focal length of the focusing lens is 2”, w_0 = 17 μm, t_0(FWHM) = 7.5 nsec.

BULK OPTICAL BREAKDOWN WITH SBS

We used 2" focal length focusing lens, D1 fused silica, w_0 = 17 μm, t_0(FWHM) = 7.5 nsec.

- Linearly polarized light: P_{th}=1279907 ± 10459 Watts, I_{corr}(lin)=(401.9 ± 3.3) GWatts/cm² (corr. for sf only).
- Circularly polarized light: P_{th}=1402577 ± 26777 Watts, I_{corr}(cir)=(405.6 ± 7.7) GWatts/cm² (corr. for sf only).
- SBS threshold is P_{th}(lin)=851021 ± 2878 Watts, P_{th}(cir)=852161 ± 2284 Watts.

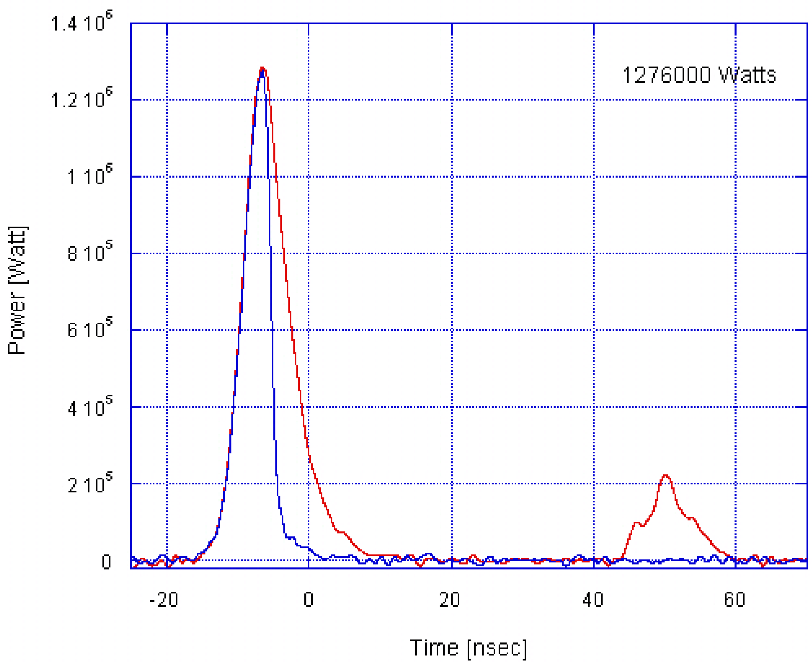


Figure 12: Incident and transmitted waveforms in a SBS assisted optical breakdown.

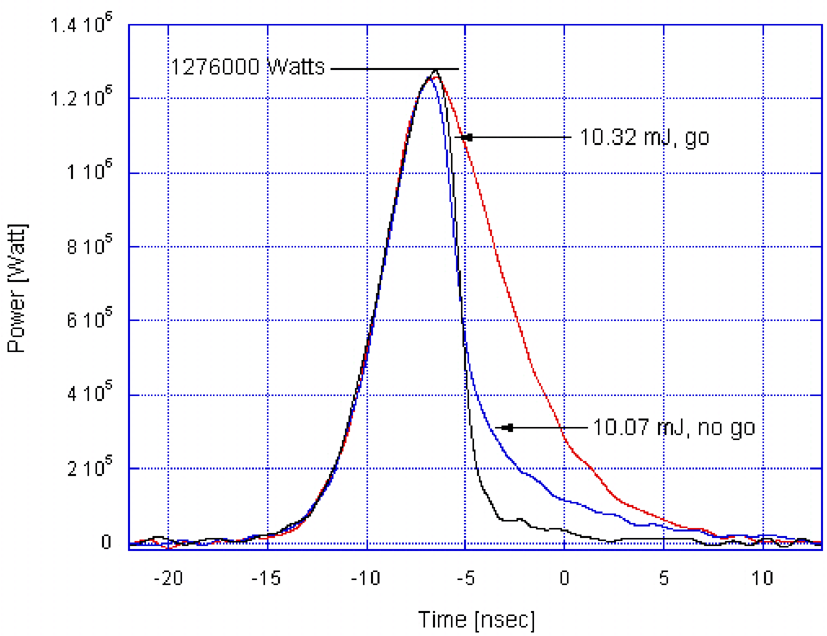


Figure 13: Comparison of the transmitted waveforms of SBS only and SBS assisted optical breakdown .

CONCLUSIONS

In order to get a true optical damage threshold we need:

- To keep damage threshold power below the SBS threshold by keeping the focusing spot small. For fused silica, at t_0=7.5 nsec, keep w_0<12.7 μm, otherwise, SBS will affect the damage threshold.
- To do a self focusing correction.

3. LOCATION AND SIZE OF THE LASER FOCUS

Putting beam waist on the sample's surface	Uncertainty (μm)	Destructive
Surface third harmonic method	<10 (w_0 = 7.45 μm)	No
Z-scan surface optical breakdown	~40 (w_0 = 7.45 μm)	Yes

Beam waist measurement	Uncertainty (%)	Time (hour)
Surface third harmonic method	~1	2
Razor blade method	~1	8

Advantages: We used the same sample and set up for beam waist measurement, locating the beam waist and optical breakdown study.