

# PLASMA DYNAMICS DURING BULK DAMAGE OF BOROSILICATE GLASS GENERATED BY 1.064 $\mu\text{m}$ NANOSECOND LASER PULSES

SAND2013-7780C

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*Boulder Damage Conference*  
*Boulder, Colorado, Sept. 22 - 25, 2013*

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This work was performed in part under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

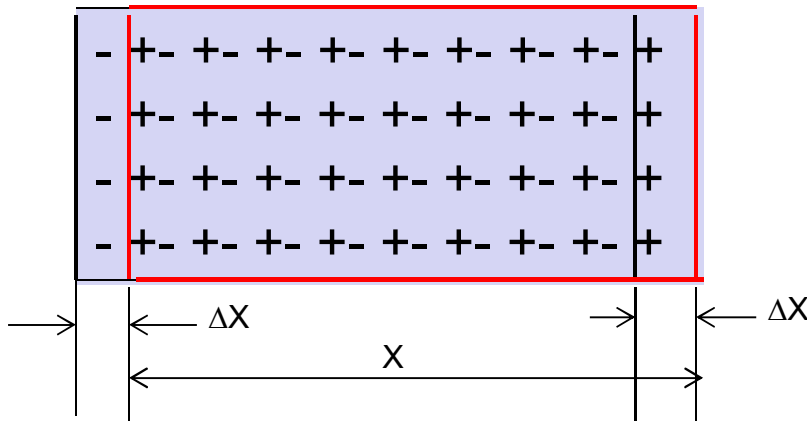
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# MOTIVATION

- Recent work has provided evidence that plasma formation precedes optical damage generated by nanosecond laser.
  - “Material response during nanosecond laser induced breakdown inside of the exit surface of fused silica”, S. Demos, R. Negres, R. Raman, A. Rubenchik, and M. Feit, Laser Photonics Review (2013).
- Modeling of optical damage has used critical plasma density (or close to it) as the damage criterion.
- Need of an experimental method to detect the critical plasma.

# A REVIEW OF PLASMA OSCILLATION

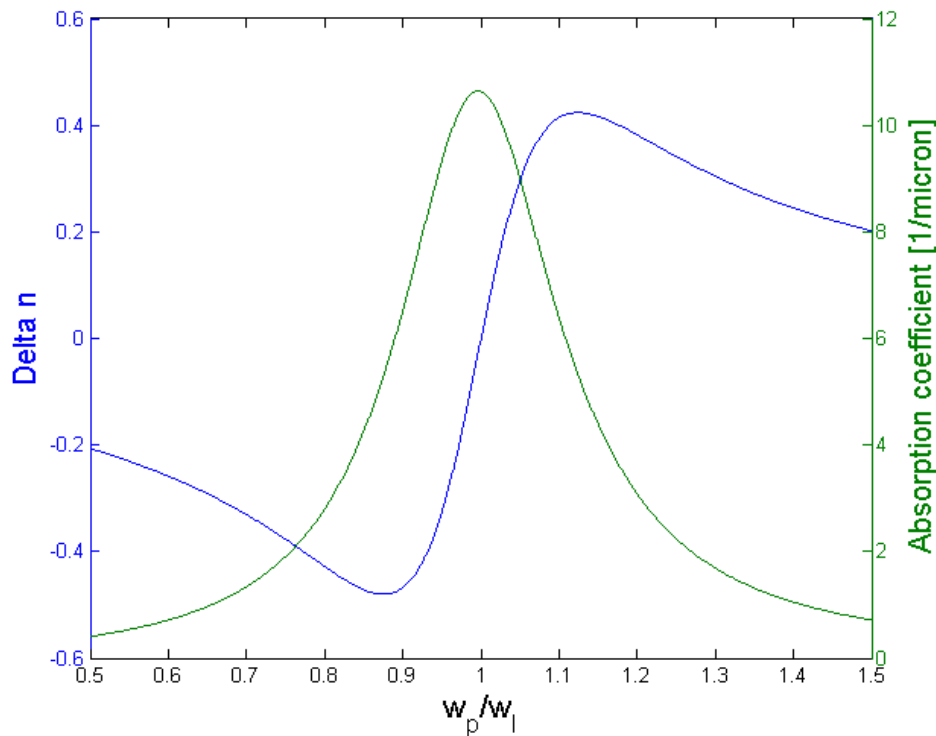
- Assume plasma is formed by the free electrons generated as the laser pulse interacts with Borosilicate glass
- The properties of such plasma can be used to validate its existence



$$\omega_p = \sqrt{\frac{ne^2}{\epsilon\epsilon_0 m}}$$

The negative electron gas can oscillate resonantly at the plasma frequency

# A REVIEW OF LASER-PLASMA INTERACTION

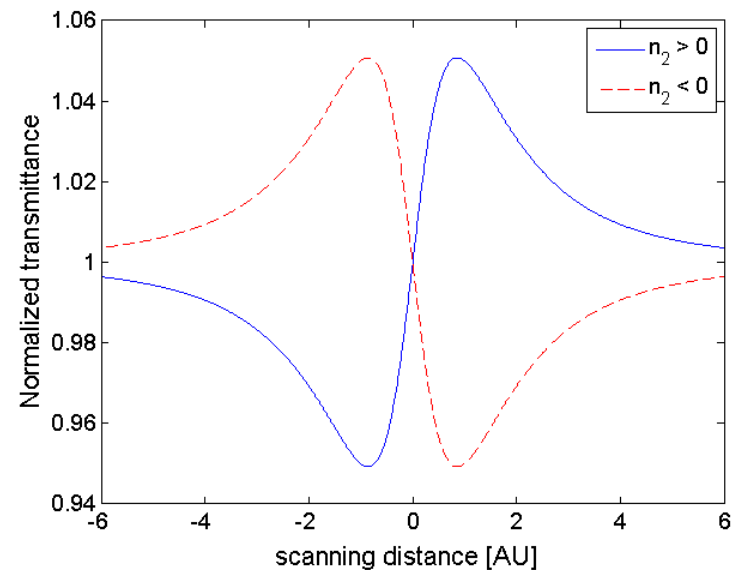
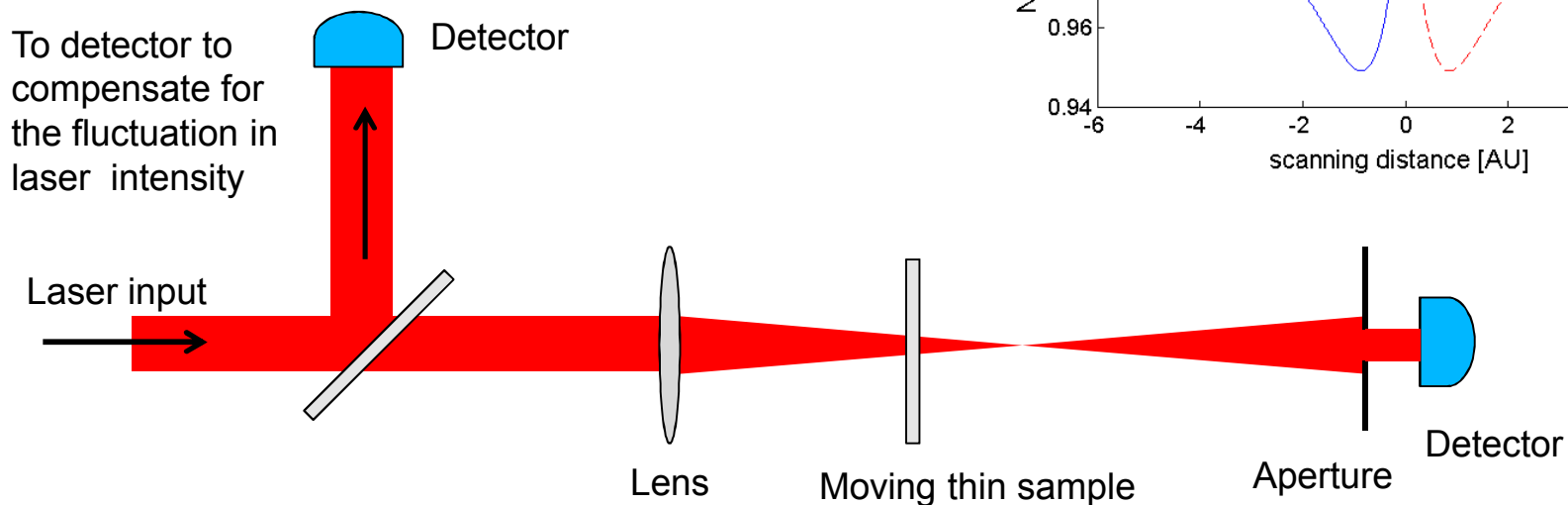


When the laser frequency becomes equal to the plasma frequency:

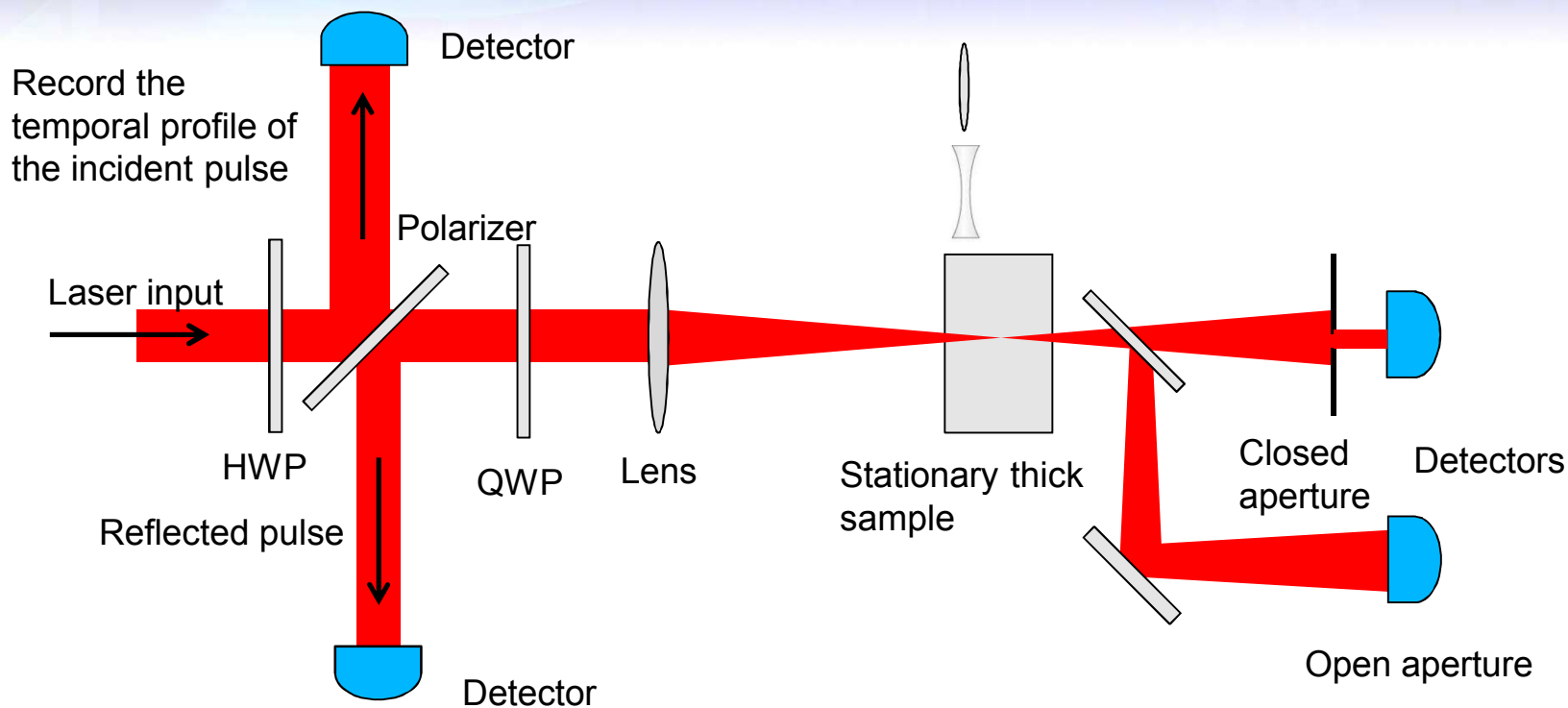
- The plasma resonantly absorbs the laser light through the collective excitation
- The absorption changes the dielectric from transparent to a totally absorbing
- This absorption is much greater than those of multiphoton and impact ionization

# DETECTION OF THE SUB-CRITICAL AND OVER-CRITICAL PLASMA

## The Z-scan method



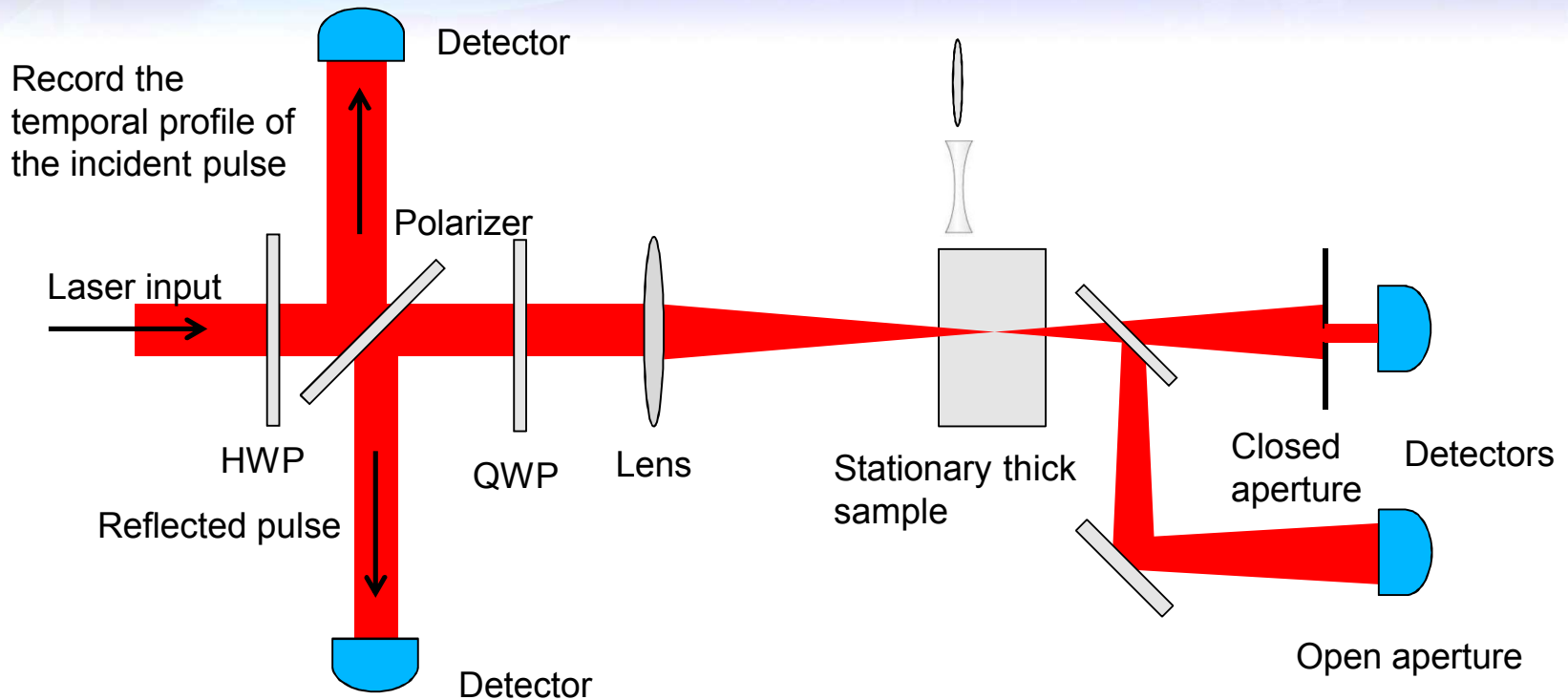
# DETECTION OF THE SUB-CRITICAL AND OVER-CRITICAL PLASMA



## Important diagnostic properties of the plasma:

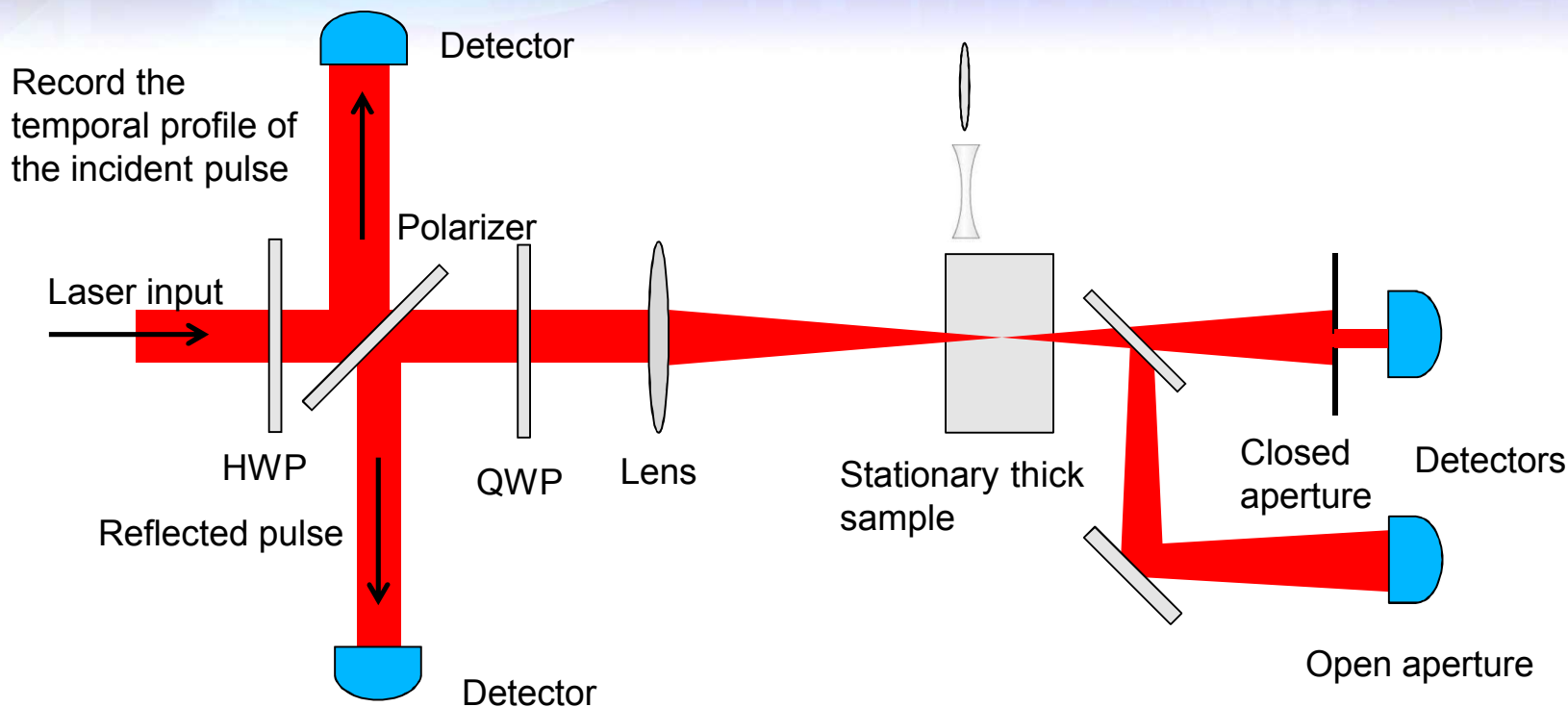
- When the free electron density is **sub-critical**, the plasma forms a weak **diverging lens**.
- When the free electron density is **over-critical**, the plasma forms a weak **converging lens**.

# DETECTION OF THE SUB-CRITICAL AND OVER-CRITICAL PLASMA



- The plasma formed at the focal point and in the region in front of the focal point depletes the laser beam.
- No appreciable plasma is formed after the focal point
- We normalize the open -aperture, close-aperture transmitted pulses by the incident pulse

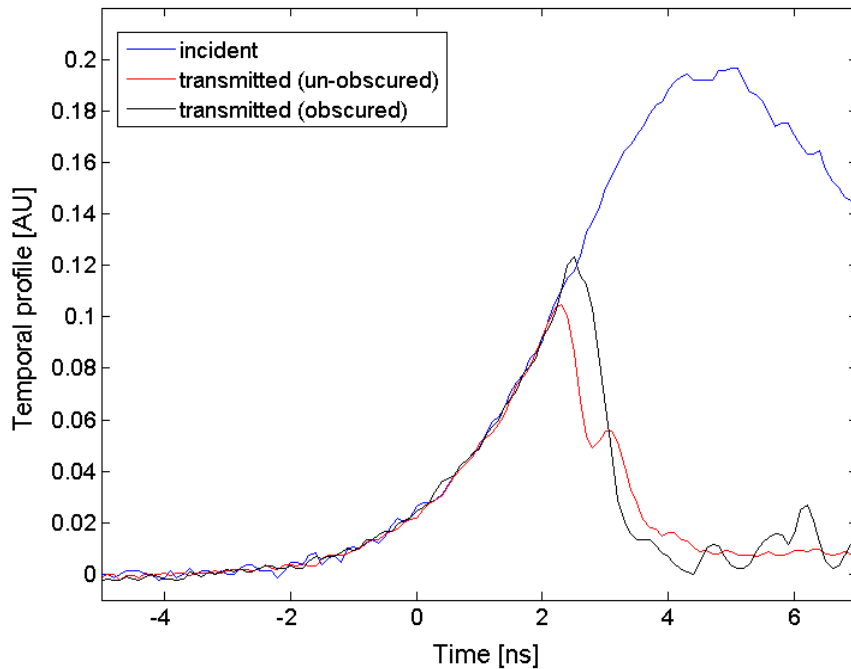
# DETECTION OF THE SUB-CRITICAL AND OVER-CRITICAL PLASMA



## Experimental design

- 8-ns FWHM, 1064 nm laser pulse, Single longitudinal mode, TEM<sub>00</sub> spatial mode
- Focus spot diameters: 15  $\mu\text{m}$  and  $\sim 7 \mu\text{m}$
- Rayleigh ranges: 250  $\mu\text{m}$  and  $\sim 54 \mu\text{m}$

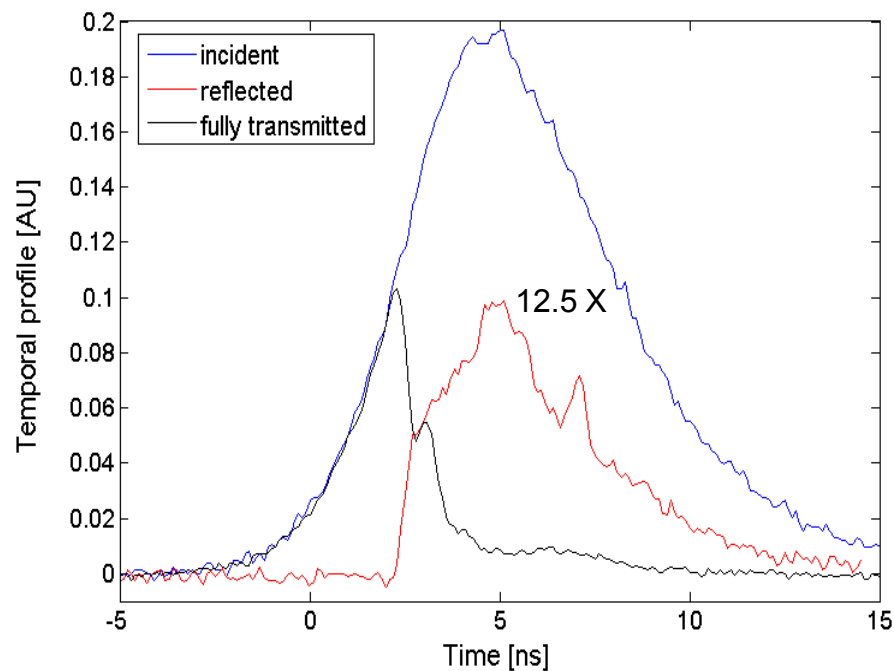
# LASER BEAM INTERACTION WITH PLASMA



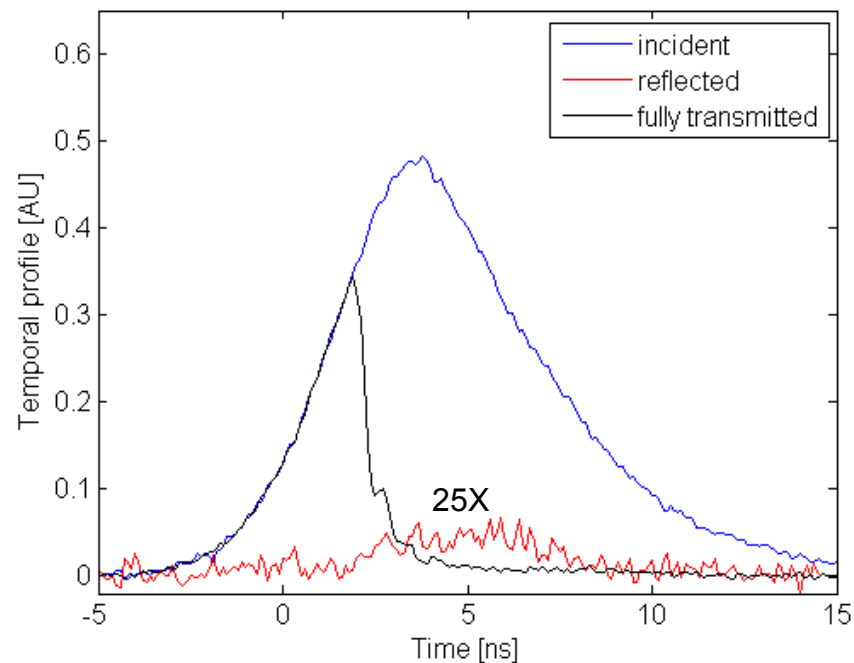
- Focus spot diameter:  $\sim 7 \mu\text{m}$
- Rayleigh range:  $\sim 54 \mu\text{m}$

- The open-aperture and close-aperture transmitted pulse is normalized by the incident pulse
- The plasma acts as a lens in front of the focal point where plasma is formed
- Enhancement of the close-aperture transmission  $\Rightarrow$  divergent lens  $\Rightarrow$  sub-critical plasma
- Decrease of the close-aperture transmission  $\Rightarrow$  convergent lens  $\Rightarrow$  over-critical plasma
- Repeatable result, intrinsic property of Borosilicate glass
- Deterministic single and multiple shot bulk damage thresholds

# DETECTION OF REFLECTED BEAM BY THE OVER-CRITICAL PLASMA

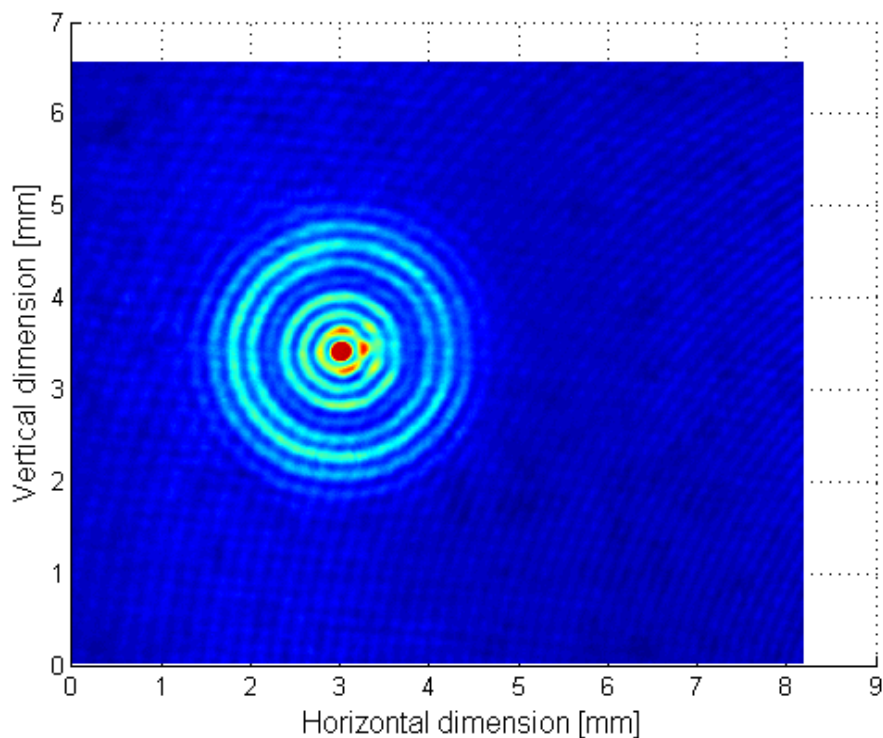


- Focus spot diameter:  $\sim 7 \mu\text{m}$
- Rayleigh range:  $\sim 54 \mu\text{m}$



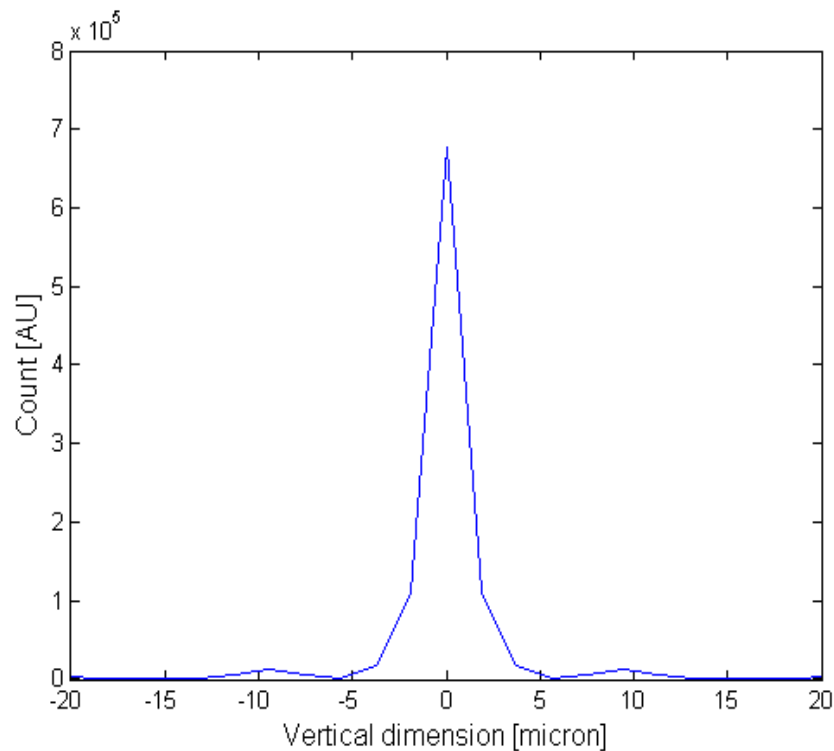
- Focus spot diameter:  $15 \mu\text{m}$
- Rayleigh range:  $250 \mu\text{m}$

# IMAGING OF THE REFLECTED BEAM BY THE OVER-CRITICAL PLASMA



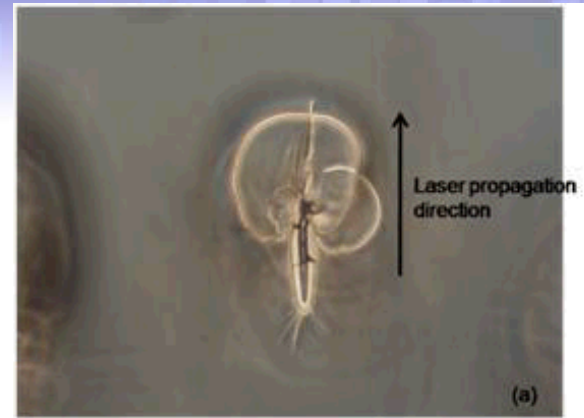
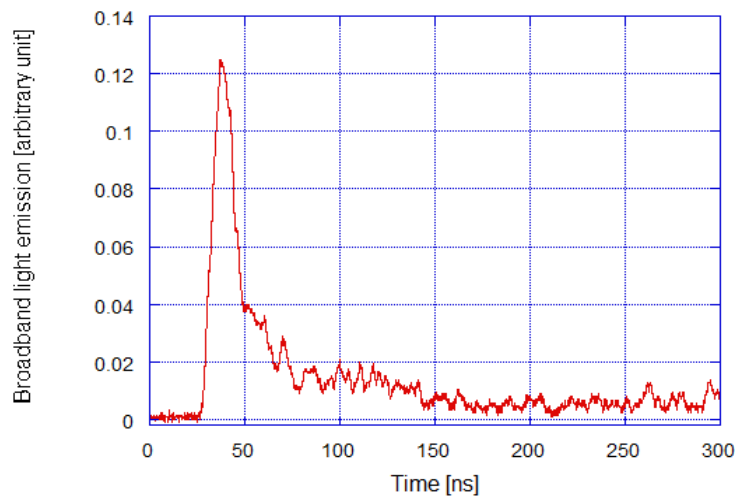
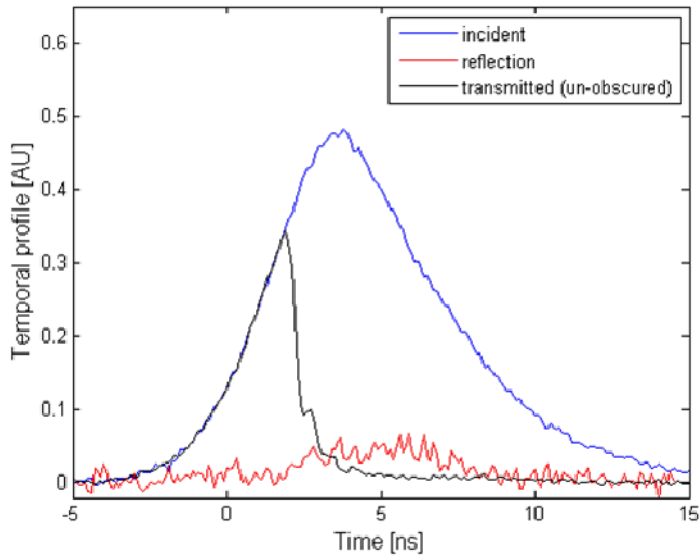
**Spatial profile of the reflected beam at the detector location**

Rayleigh range:  $\sim 54 \mu\text{m}$



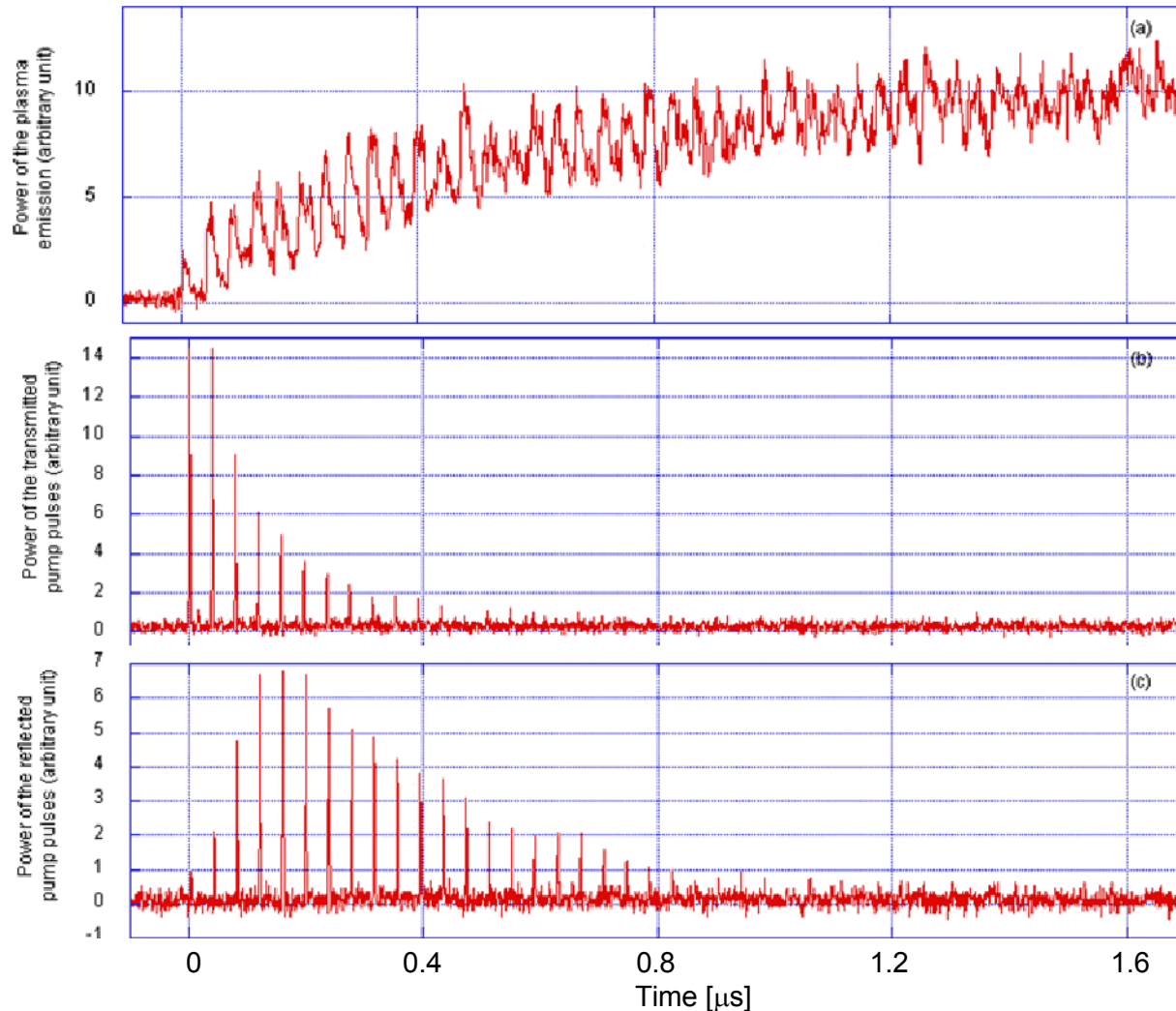
**Spatial profile of the reflected beam at the plasma location**

# OPTICAL PLASMA AND THERMAL PLASMA IN BOROSILICATE GLASS



- Most of the non-transmitted laser energy is absorbed
- The dimension of the heated volume can be found from: the damage morphology, spot size, heat diffusion length
- The temperature can be  $\sim 2$  eV and the band gap of Borosilicate glass is 4.3 eV
- The Boltzmann factor shows the thermal plasma is close to the critical density
- High density plasma can last several ten of ns after the laser pulse

# CONTINUOUS HIGH-DENSITY PLASMA IN BOROSILICATE GLASS GENERATED BY 25 MHz 100 fs LASER



- For a single shot, high density plasma can last several ten ns
- 25 MHz, 100 fs laser, generates optical breakdown single shot
- The high density plasma survived between laser shots
- The plasma can be sustained for several minutes
- For about minute or less, no physical damage, optical modification was created

# OPTICAL BREAKDOWN DOES NOT GUARANTEE PHYSICAL DAMAGE

- Physical damage in dielectric is defined as modification that alters the continuity of the material (cracks etc.)
- Change in refractive index is optical modification, it is not physical damage
- Optical breakdown transiently changes the dielectric from transparent to totally absorbing
- Whether the physical damage is created or not depends on how much energy the target absorbed after the breakdown. When the absorbed energy is low, it will not create a physical damage.
  - Short pulse  $\Rightarrow$  small amount energy deposited  $\Rightarrow$  optical modification
  - Long pulse  $\Rightarrow$  large amount energy deposited  $\Rightarrow$  physical damage
- Optical breakdown is a necessary condition but it is not sufficient to guarantee physical damage

# INCLUDING THE MISSING TERM IN THE CURRENT RATE EQUATION

## The current rate equation

$$\frac{dn_e}{dt} = \beta I^k + \alpha_I I n_e - \frac{n_e}{\tau_r}$$

## The suggested rate equation

$$\frac{dn_e}{dt} = \beta I^k + \alpha_I I n_e - \frac{n_e}{\tau_r} + \alpha_c(n_e) I$$

$$\frac{dn_e}{dt} = \beta I^k + \alpha(n_e) I - \frac{n_e}{\tau_r}$$

- $\beta I^k$ : Multi-photon ionization
- $\alpha_I I n_e$ : Impact-ionization,  $\alpha_I$  is the impact-ionization constant
- $n_e/\tau_r$ : Recombination
- Collective excitation becomes dominant when  $n_e$  is 100 times (or more) smaller than the critical density
- Suggest to add  $\alpha_c(n_e) I$  to take into account the free electrons generated by the energy absorbed through the collective excitation
- Combine the two terms  $\alpha_I I n_e$  and  $\alpha_c(n_e) I$  into  $\alpha(n_e) I$ .

# CONCLUSIONS

- Show the experimental evidence that plasma formation is the first step in the damage process arising from exposure to  $1.064 \mu\text{m}$  ns laser pulses in bulk Borosilicate glass
- The plasma changes from sub-critical to over-critical
- The critical and close to critical plasma transforms the glass from transparent to total absorbing in a ns or less
- The plasma-reflected laser beam was experimental measured
- Optical breakdown is necessary but not sufficient condition to create observable physical damage.
- We have introduced a more complete rate equation for optical breakdown

# ACKNOWLEDGEMENTS

- Fiber grand challenge LDRD of Sandia National Laboratories.
- Support from members of the Laser, Optics and Remote Sensing Department of Sandia National Laboratories.

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