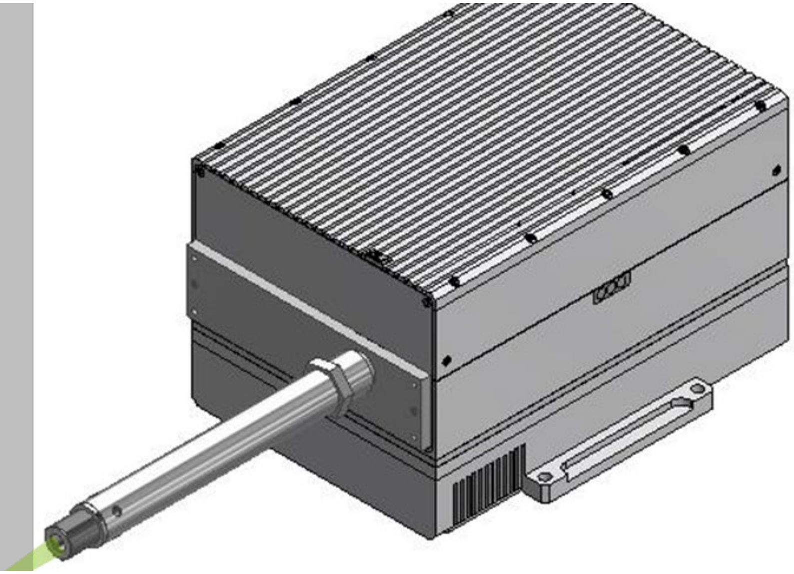
PAPER 011
THE 9TH INTERNATIONAL SUPERCRITICAL $CO_2$ ENERGY TECHNOLOGIES SYMPOSIUM

# LASER IGNITER DEVELOPMENT FOR $SCO_2$ COMBUSTORS



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** Patent pending **

March 3, 2026

Development

Demonstration

Lens Fouling Mitigation

Δη = 2.6%

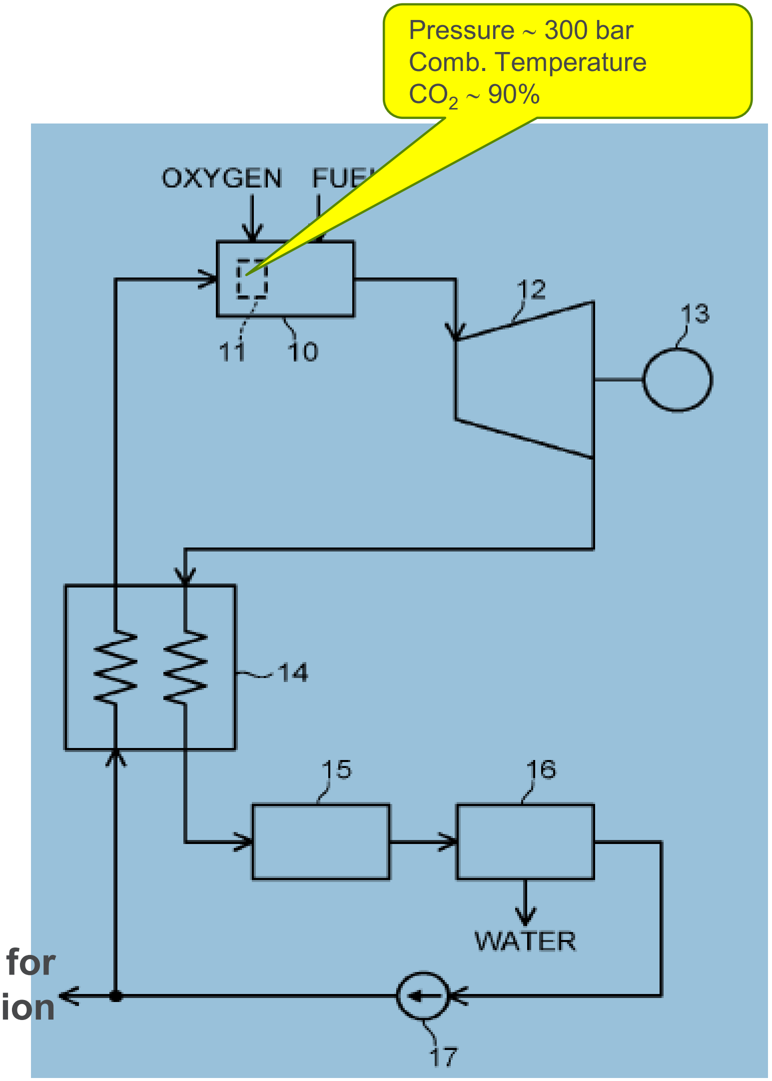
Current spark plug regap interval
1000 – 3000 hrs.

Projected service interval (Recent tests)
> 6000 hrs. @ 1800rpm

ARES program target
~ 8000 hrs.

# ALLAM-FETVEDT CYCLES OFFER SEVERAL ADVANTAGES

- Power generation using fossil fuels at highly competitive rates
  - Natural gas
  - Coal derived syngas
- Carbon sequestration
- No cooling water required, i.e., dry-cooling is possible
- Extremely compact hardware that significantly reduce the footprint as well as the maintenance costs
- Near-zero emissions

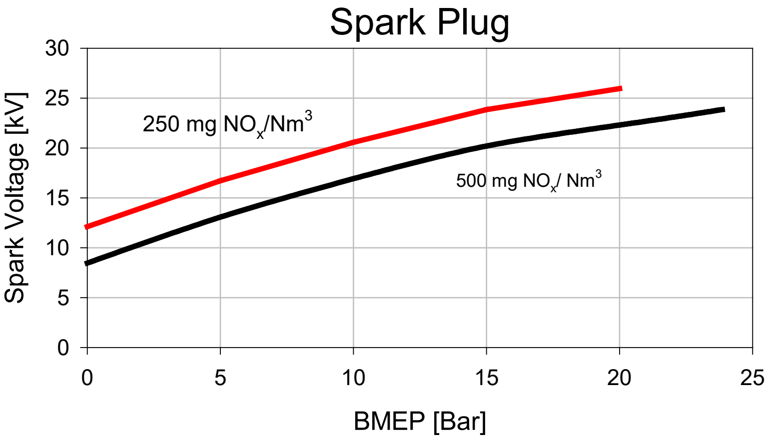


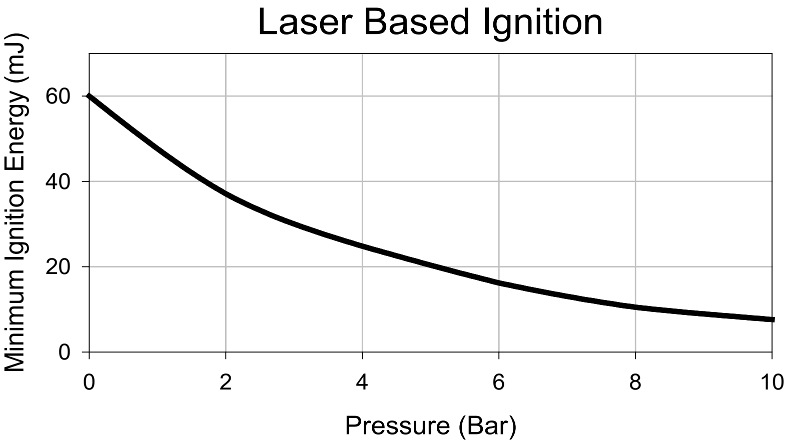
Pressure ~ 300 bar
Comb. Temperature
$CO_2$ ~ 90%

**Pressurized $CO_2$ for Sequestration**

*** Harsh combustor conditions are extremely difficult to ignite**

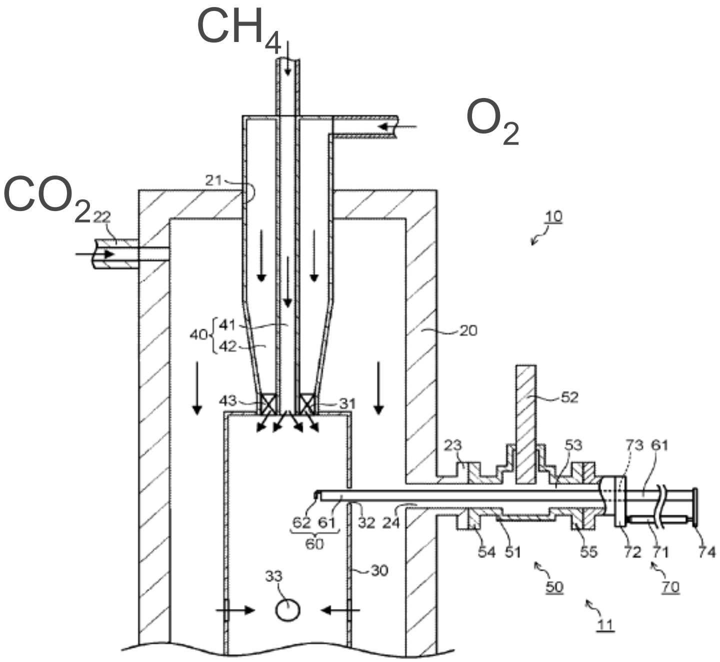
# WHY LASER IGNITION?



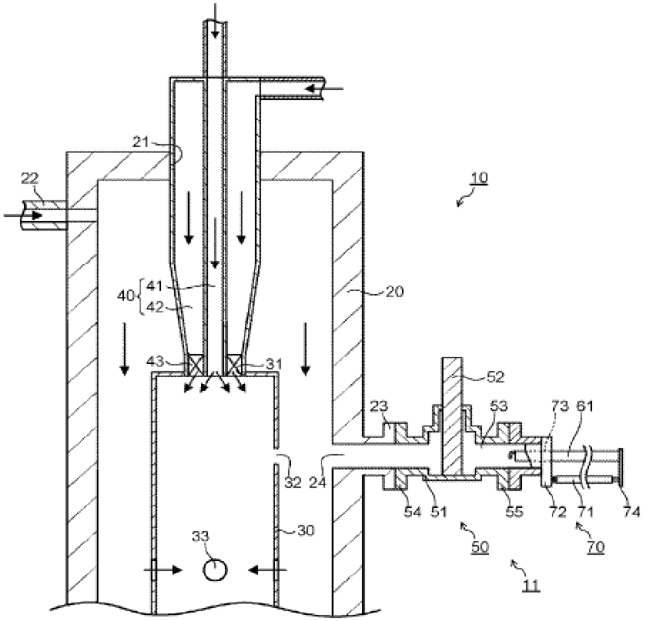


1) Easier ignition at higher pressures
   - Unlike spark igniters, higher pressures improve photon-molecule interactions and facilitate easier plasma kernel generation with laser ignition
2) Spatially & temporally distributed ignition
3) Significant reduction in plant restart time in the event of a flame blow-off
   - Current practice: reduce pressure to ~20 bar from 300 bar, ignite, and slowly ramp up to full load again.
   - Laser ignition may enable instant restart under high-load conditions.
4) Remotely located hardware that does not perturb the flow field
5) Enables use of a variety of gaseous fuels & higher dilution conditions ($CO_2$ %).

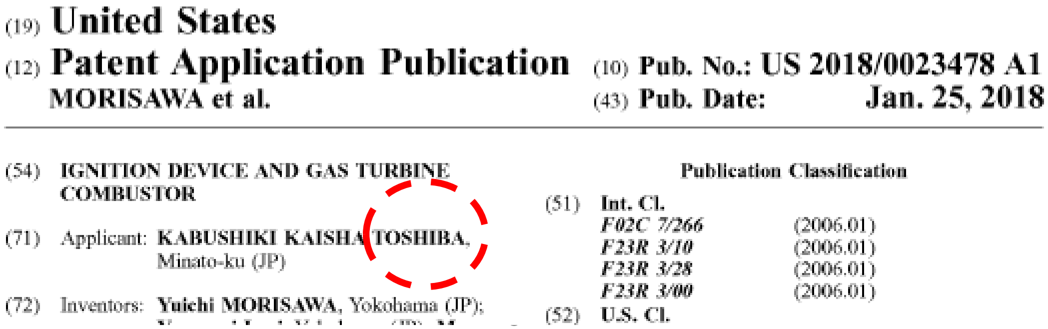
# A RETRACTABLE IGNITER OFFERS SOME RELIEF



**Extended position**



**Retracted**



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**MORISAWA et al.**

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(43) **Pub. Date: Jan. 25, 2018**

(54) **IGNITION DEVICE AND GAS TURBINE COMBUSTOR**

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**Publication Classification**

(51) **Int. Cl.**

| | |
|---|---|
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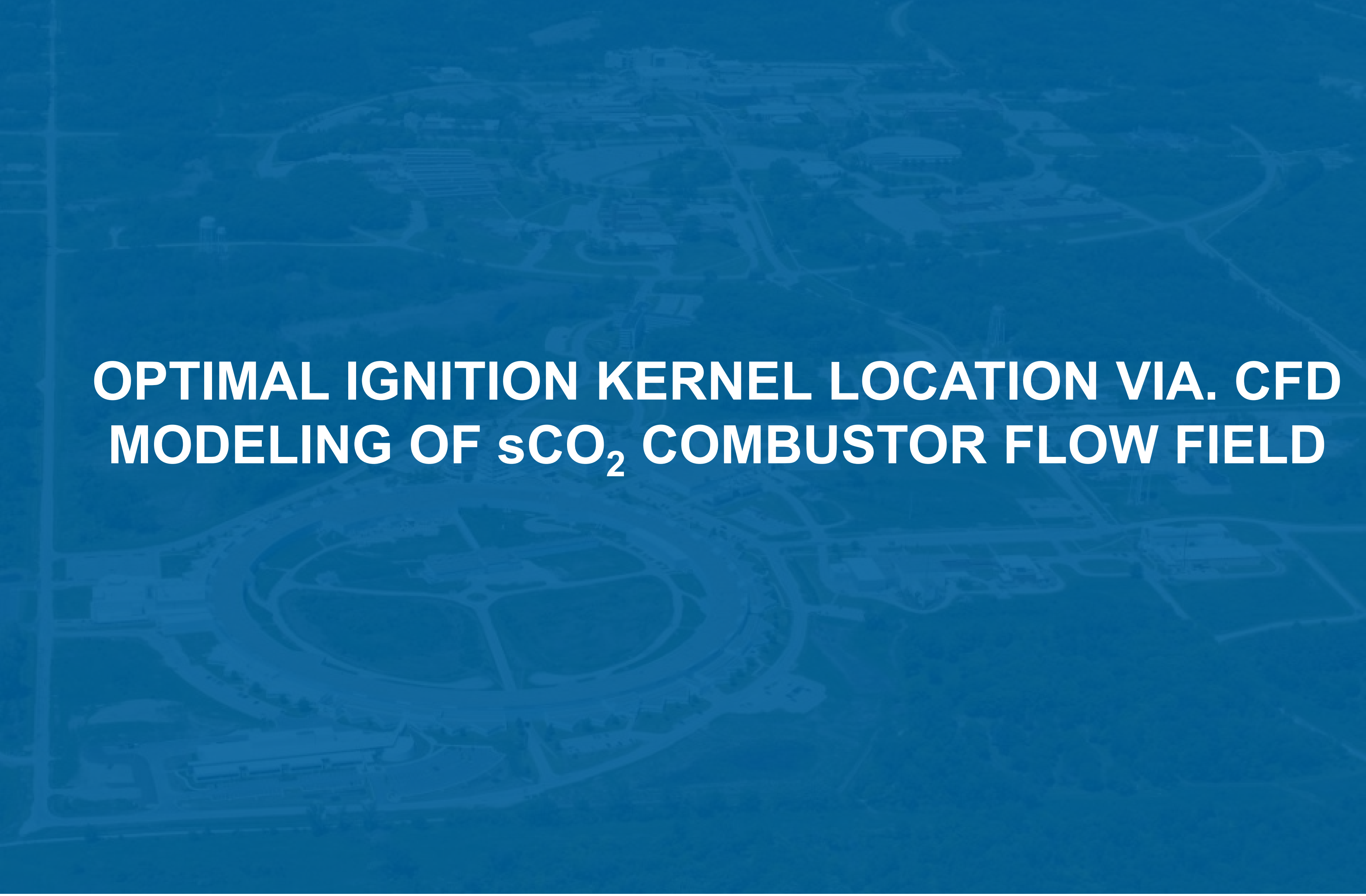
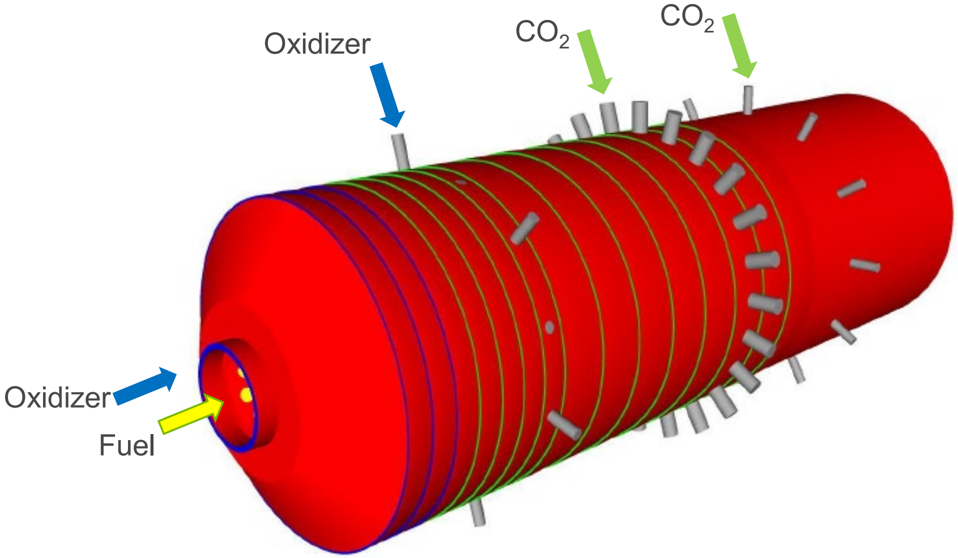
| *F23R 3/10* | (2006.01) |
| *F23R 3/28* | (2006.01) |
| *F23R 3/00* | (2006.01) |

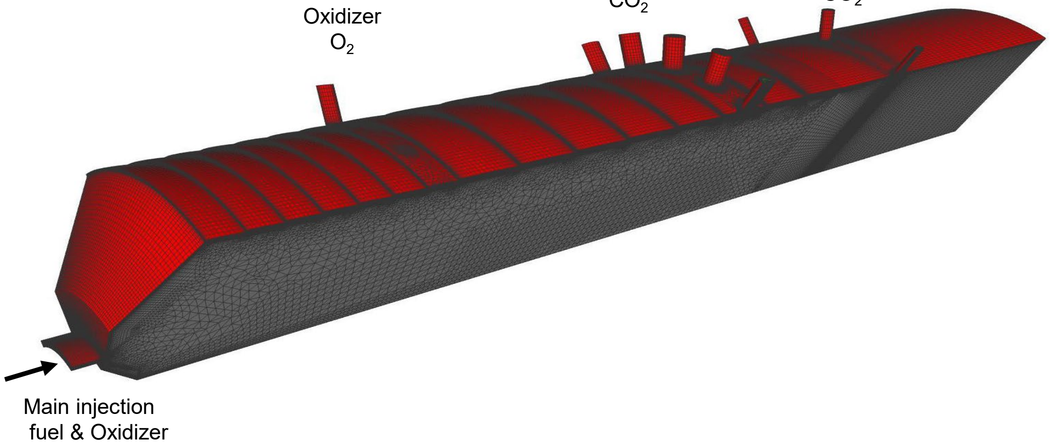
(52) **U.S. Cl.**



# OPTIMAL IGNITION KERNEL LOCATION VIA. CFD MODELING OF $sCO_2$ COMBUSTOR FLOW FIELD

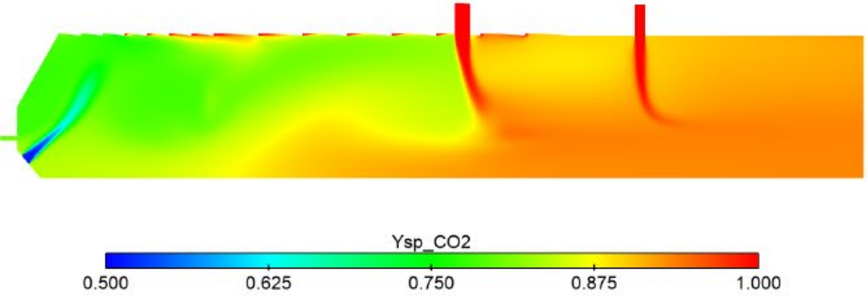
# 8RIVERS 50MWTH COMBUSTOR GEOMETRY



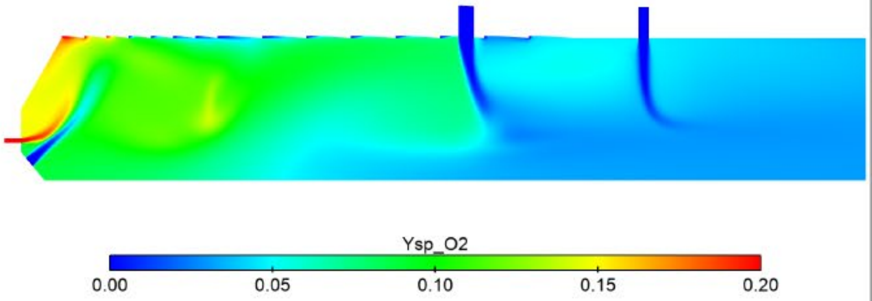


# 20 BAR
# SRK EOS RESULTS: CUTTING PLANE $\theta$ =90°

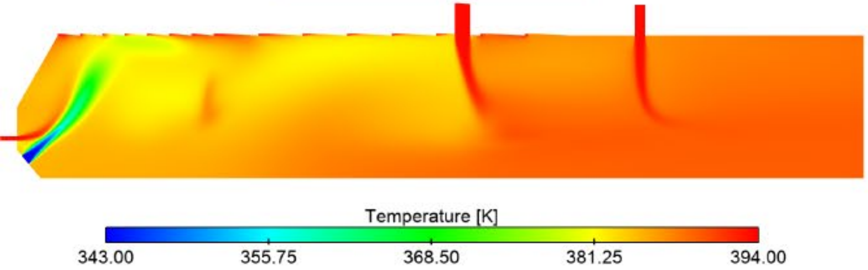
**$CO_2$ Mole Fraction**



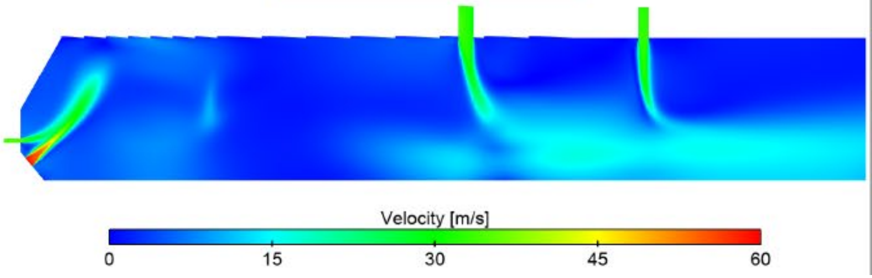
**$O_2$ Mole Fraction**



**Temperature [K]**



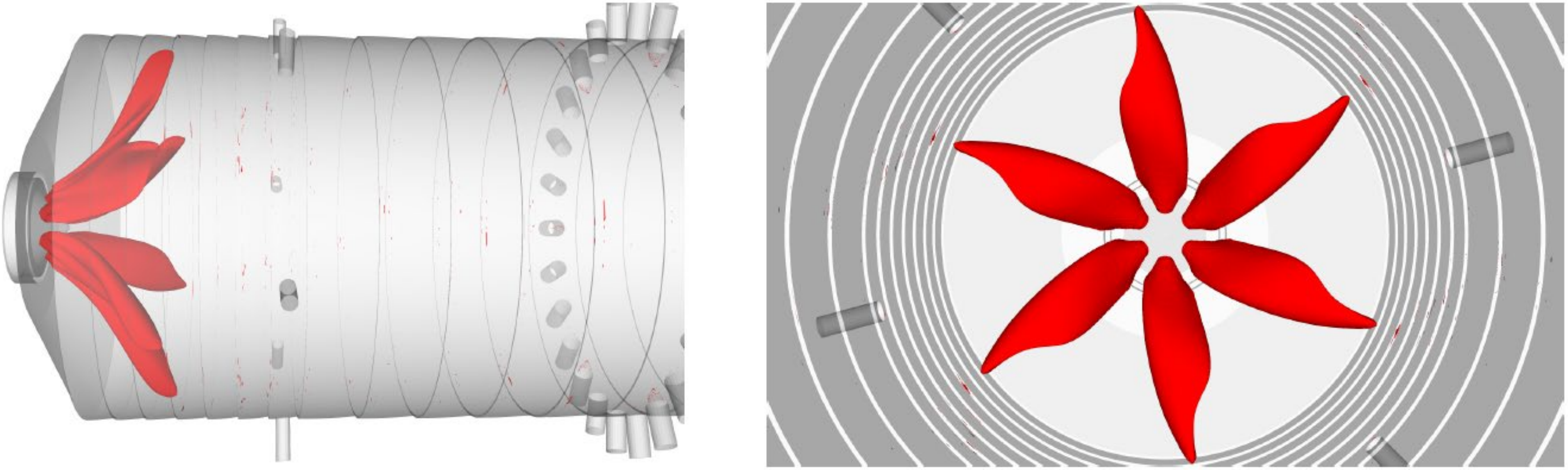
**Velocity [m/s]**



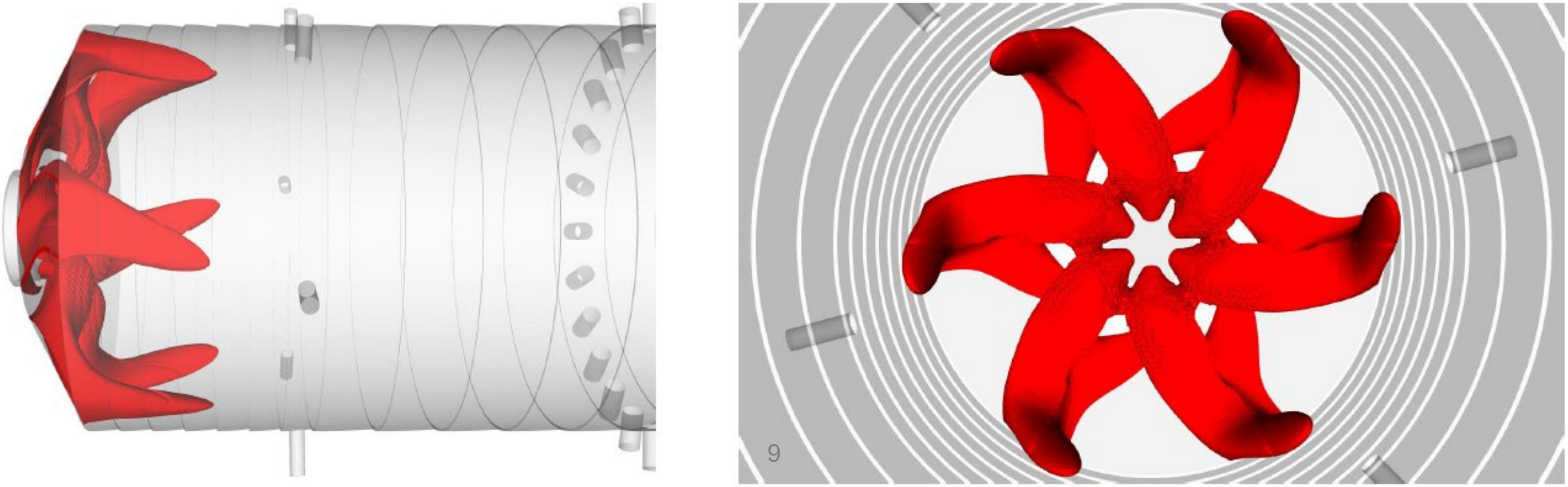
# ISOVOLUMES PRIOR TO IGNITION
# $\phi$ = 0.95-1.05

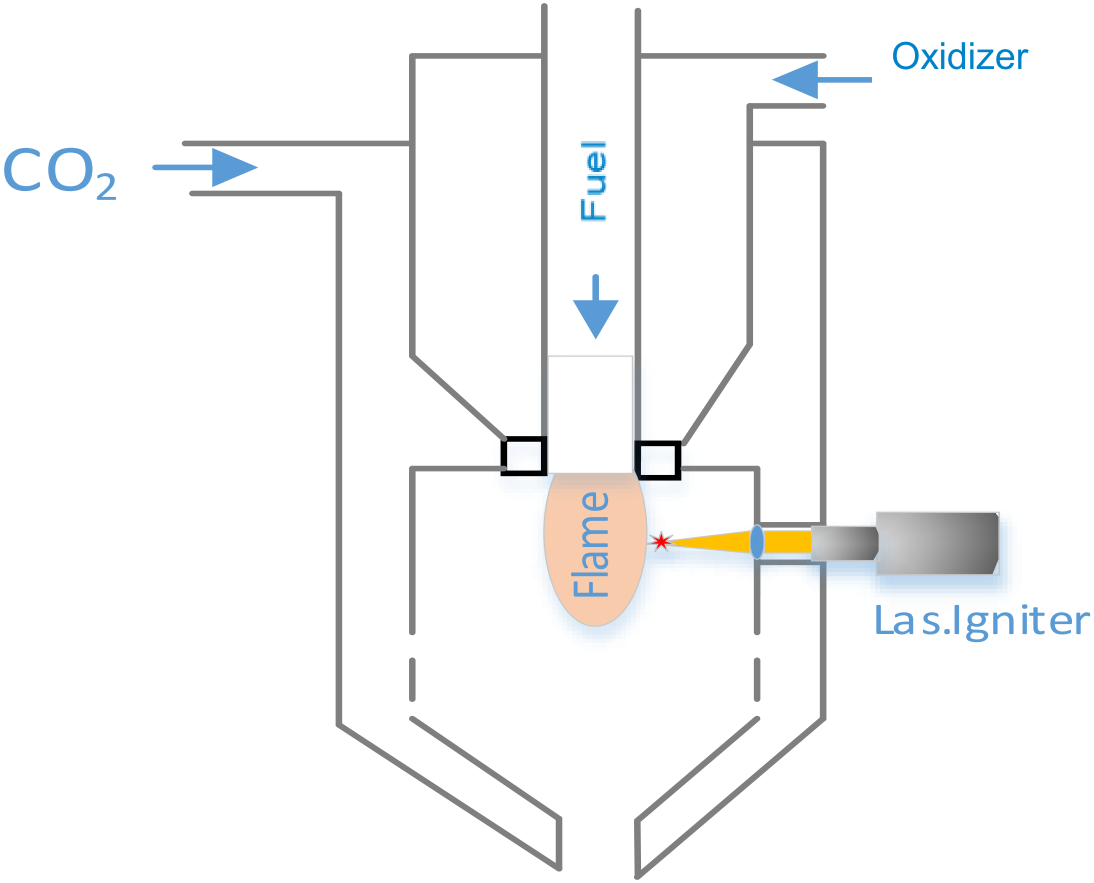
$$\varphi = \frac{\frac{F}{Ox}}{\left(\frac{F}{Ox}\right)_{stoic}} = \frac{\frac{Y_{H2}+Y_{CO}}{Y_{O2}}}{2}$$

**20 Bar**



**300 Bar**

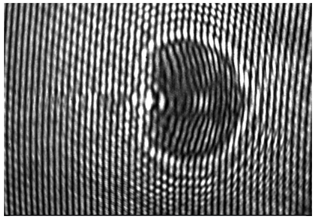


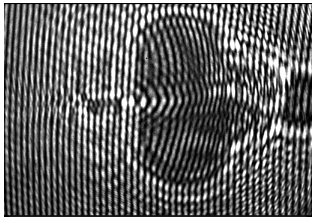

Oxidizer
$CO_2$
Fuel
Flame
Las.Igniter

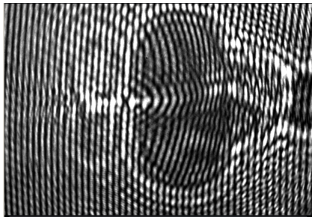
# LASER IGNITER DESIGN & DEVELOPMENT

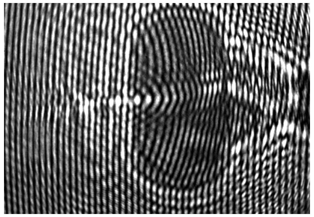
# INTERFEROGRAMS

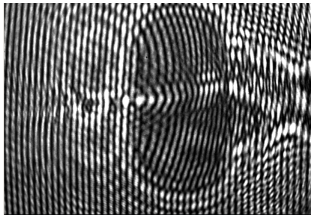
Methane/air; 2 bar, $\phi = 0.65$
(ms from laser incidence)

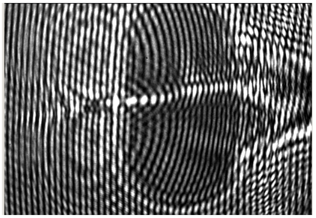

0.05

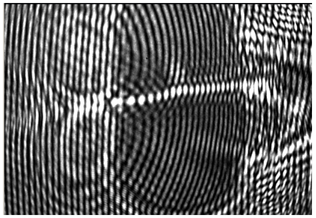

0.15

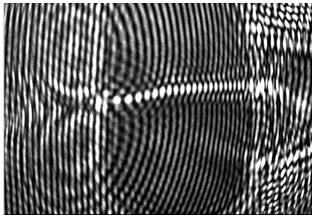

0.25

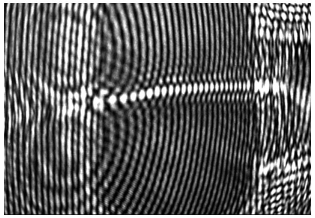

0.35

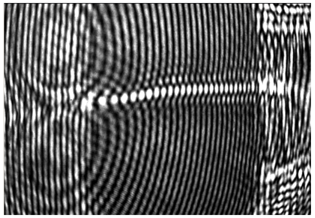

0.45


0.65

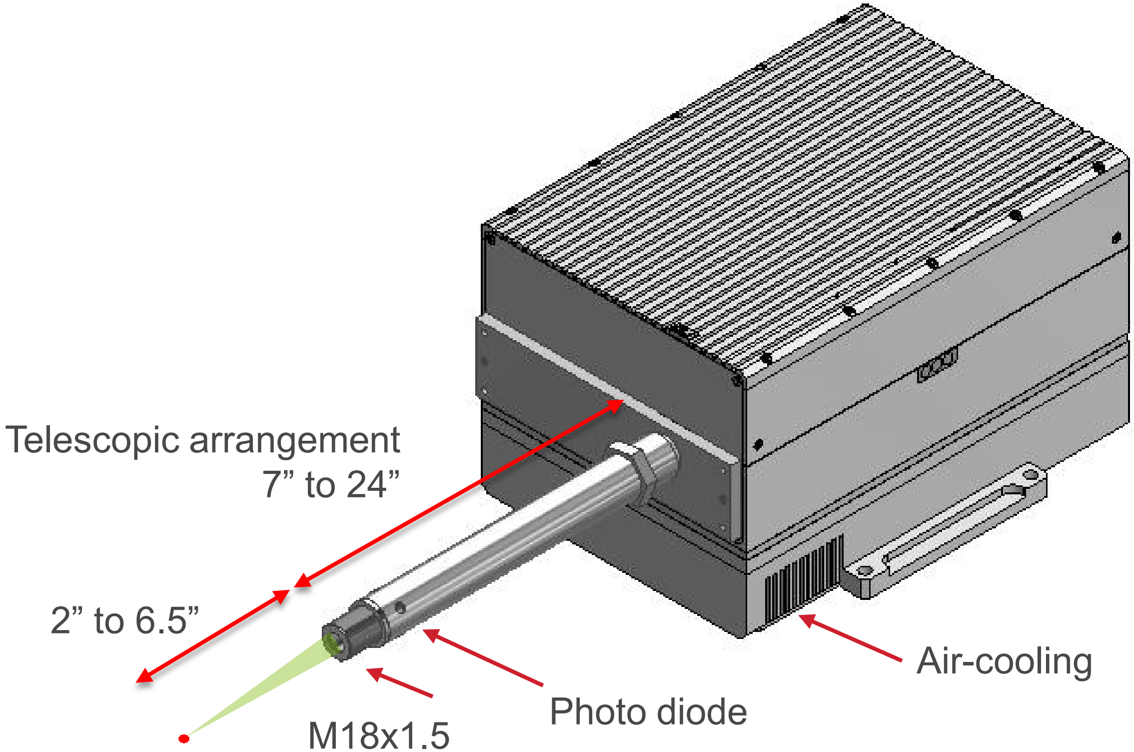

1.00


1.50


2.00


2.50

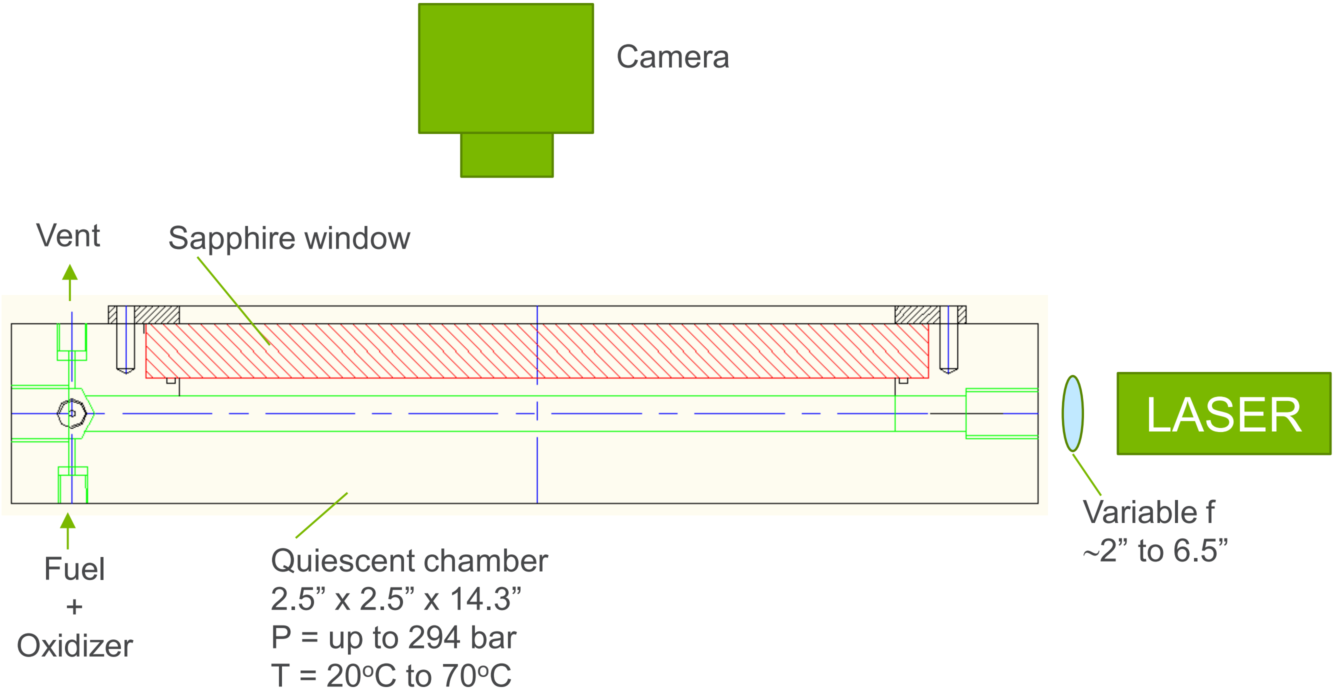
(1) Pressure
(2) Temperature
(3) Velocity
(4) Equivalence ratio
(5) $CO_2$ concentration


Telescopic arrangement
7” to 24”
2” to 6.5”
Air-cooling
Photo diode
M18x1.5

# DESIGN SPECIFICATIONS

| Design targets for performance of sCO2 laser igniter | |
|---|---|
| **Flow field Pressure** | up to 300 bar |
| **Flow field Temperature** | typical of combustion |
| **Flow field Velocity** | up to 30 m/s |
| **Equivalence ratio,** $\phi = (F/O)/(F/O)_{Stoic}$ | Range TBD |
| **Dilution by** $CO_2$ | Range TBD |
| | |
| **Distance from igniter tip to ignition kernel** | up to 165mm |
| **Foot print** | M18 x 1.5mm |
| | |
| **Ambient pressure** | 1 atmosphere |
| **Ambient temperature / cooling requirement** | Air-cooled up to 30°C; requires water cooling for $T_{amb} > 30°C$ |
| **Spark plug well temperature / casing temperature** | Max. 700°C |
| | |
| **Power requirement** | 12VDC or 28VDC; 50 Watts |
| **No. of Ignitions** | > 5000 |
| **Laser** | Class-IV; pulsed laser delivering up to 20 consecutive pulses @50Hz |

# IGNITION TESTS FOR PERFORMANCE EVALUATION



Camera

Vent

Sapphire window

LASER

Fuel
+
Oxidizer

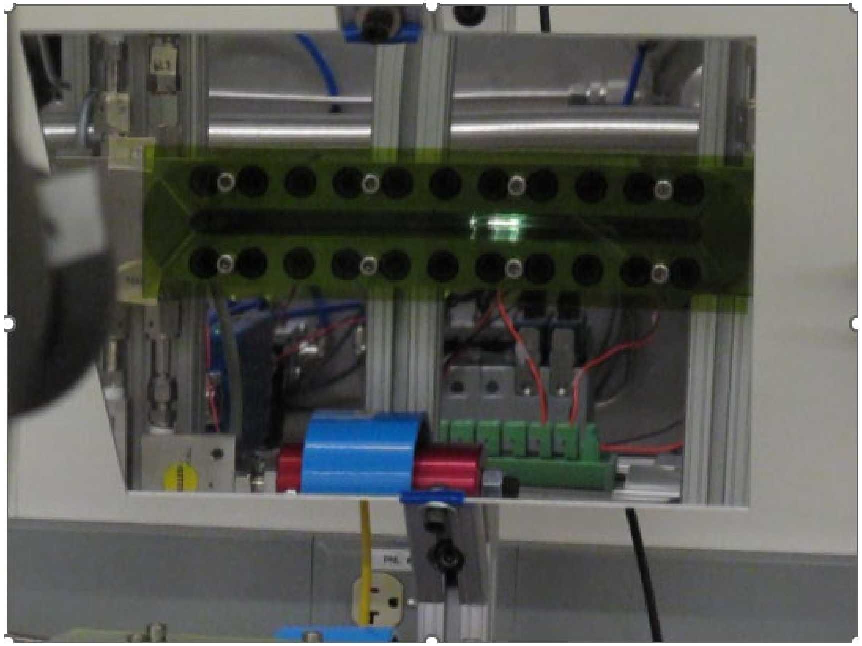
Quiescent chamber
2.5” x 2.5” x 14.3”
P = up to 294 bar
T = 20$^{o}$C to 70$^{o}$C

Variable f
~2” to 6.5”

# IMAGING IN NON-COMBUSTION ENVIRONMENTS

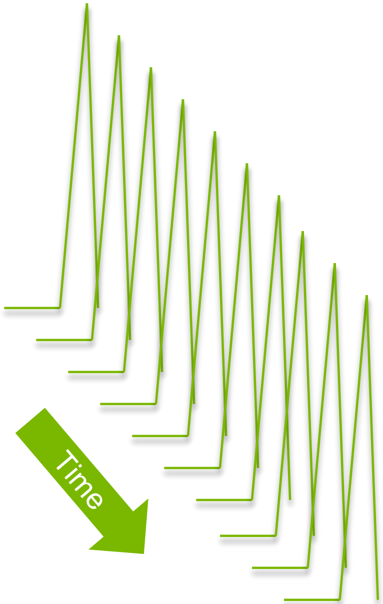
## In compressed air

# MULTI-PULSE & VOLUMETRIC IGNITION POSSIBLE WITH LASER IGNITION



10 Hz, f = 150 mm

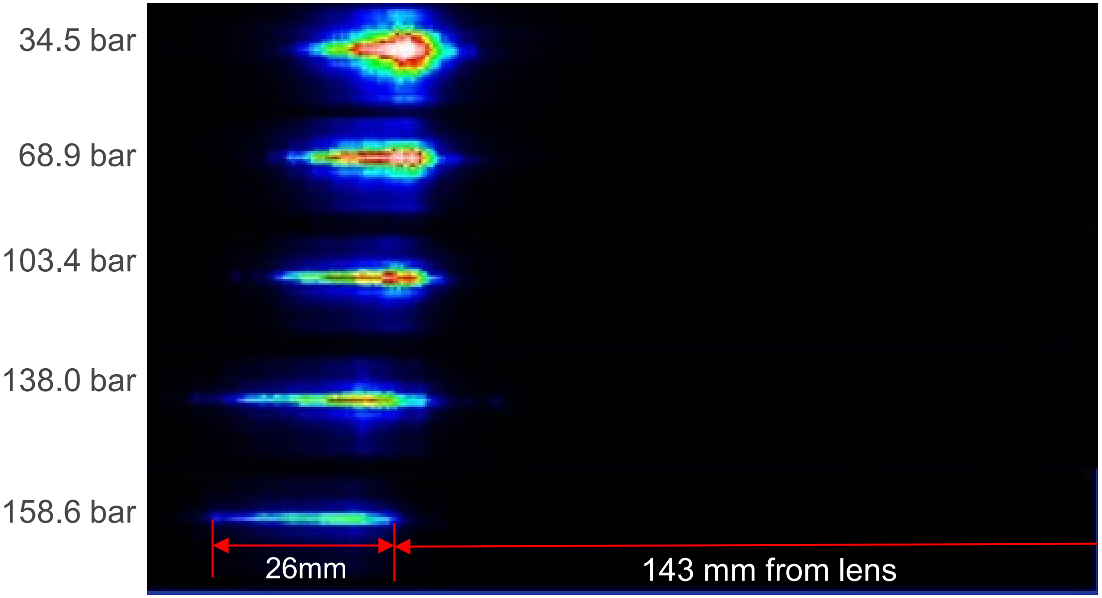
- Multiple ignition kernels per shot
- Spatial distribution spread over 26mm



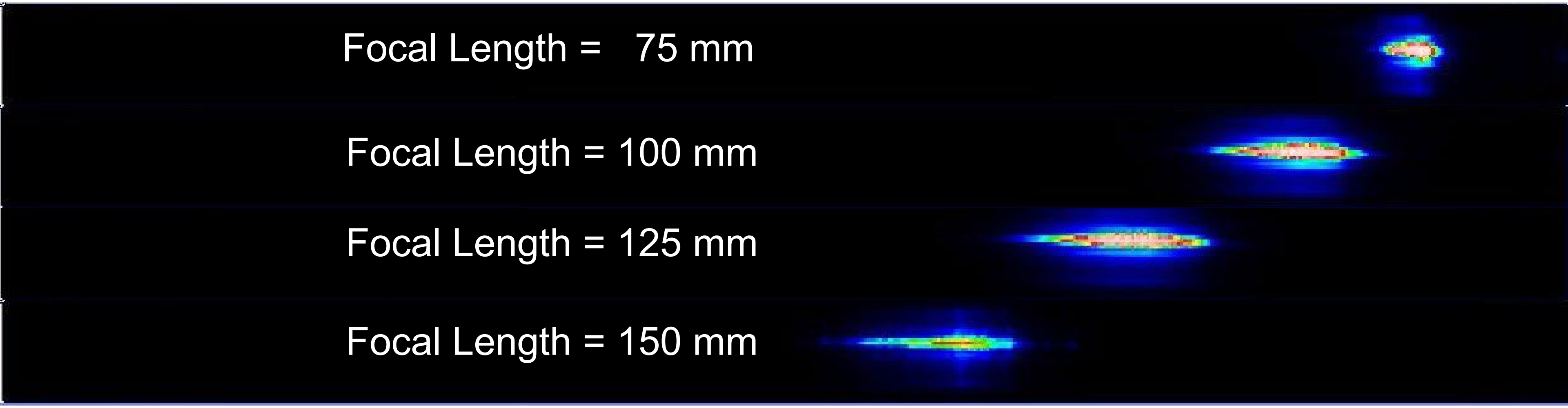
Burst (50 Hz, 10 pulses ), f = 150 mm

- Temporal distribution
- Higher ignition probability

# Focal length = 150 mm; compressed air
# Composite Image of 20 shots



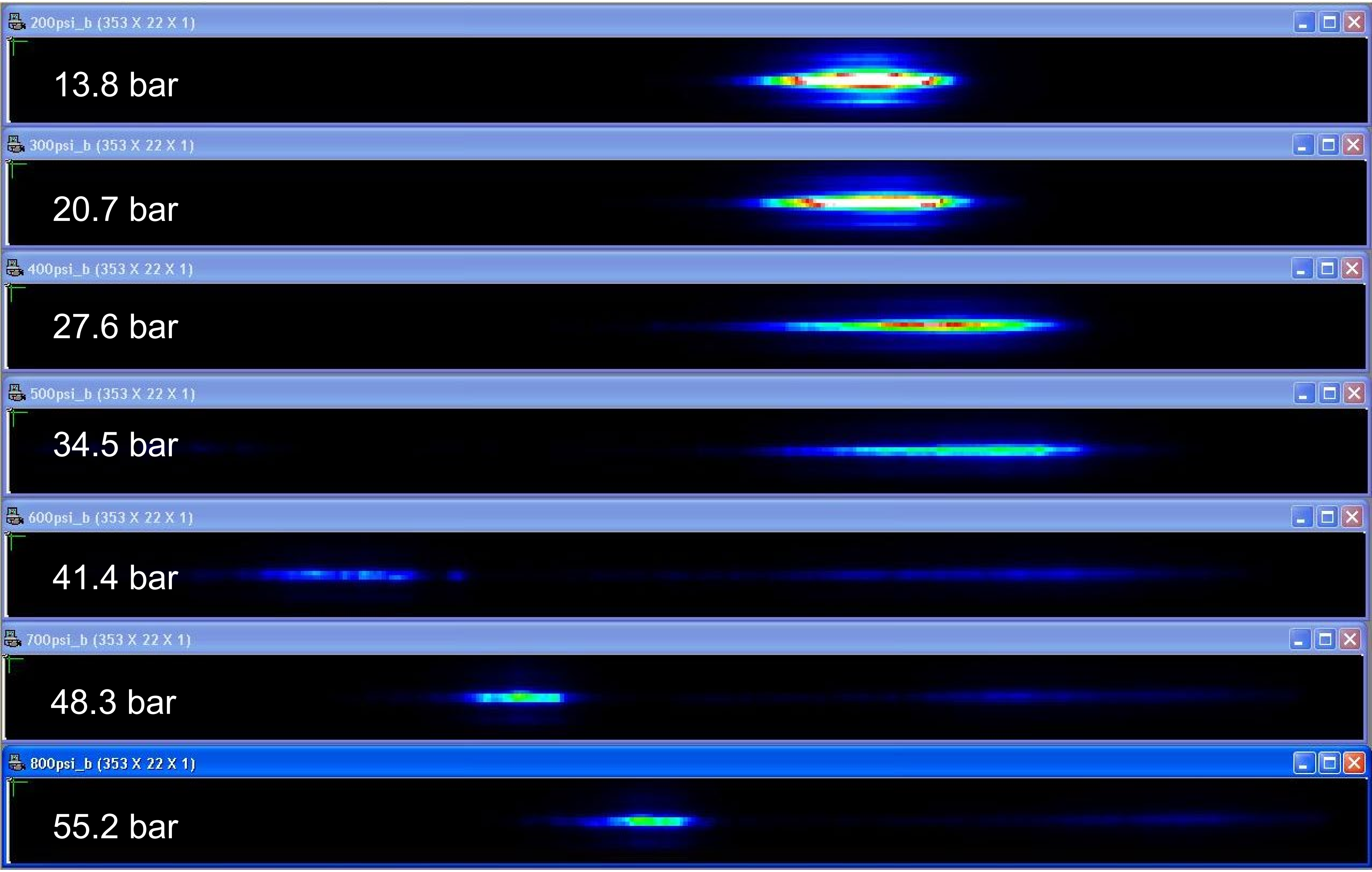
## Compressed Air @ 2000 psi ($\rho$=164 kg/m3)
## Composite image of 20 shots



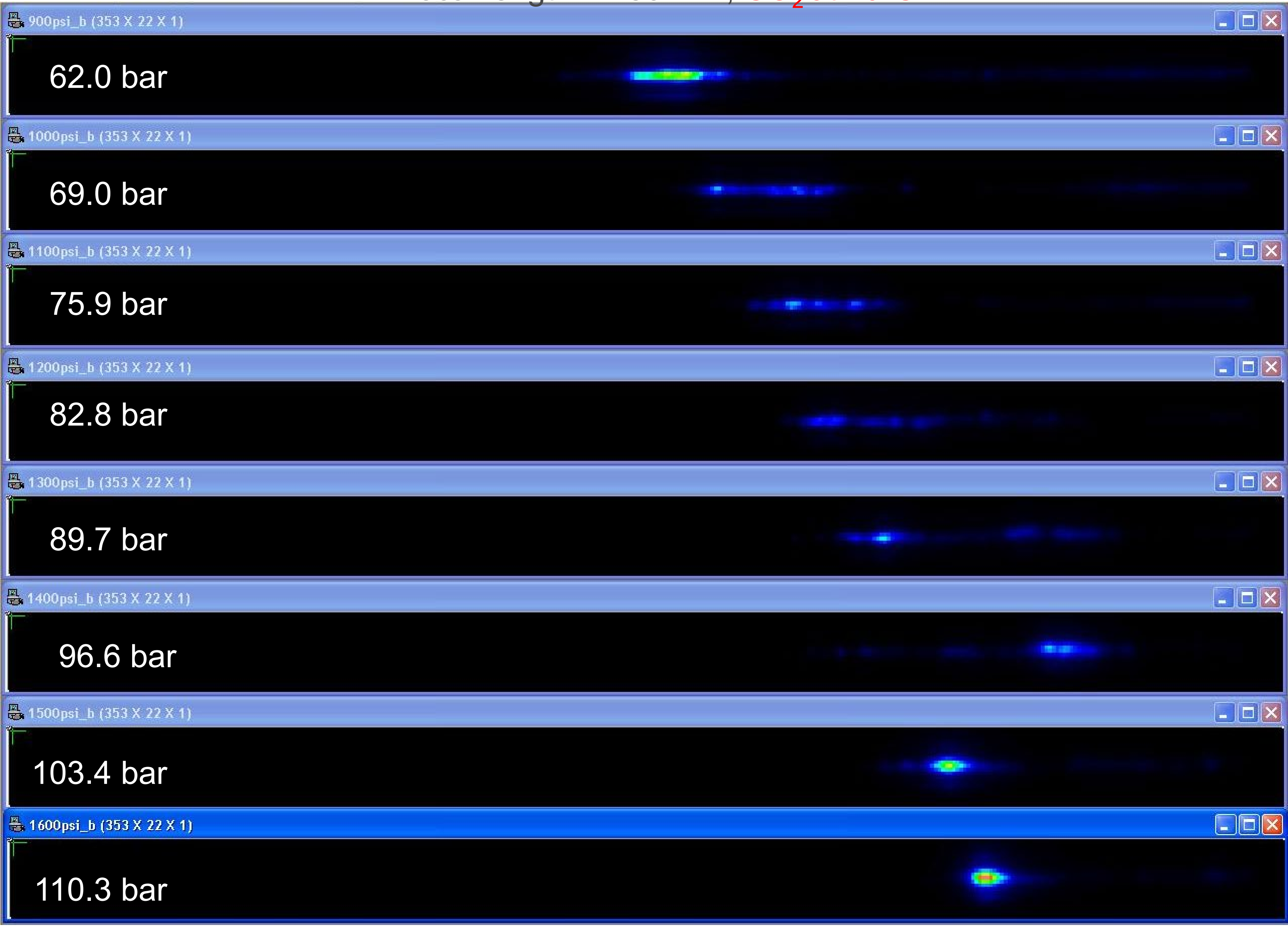
# IMAGING IN NON-COMBUSTION ENVIRONMENTS

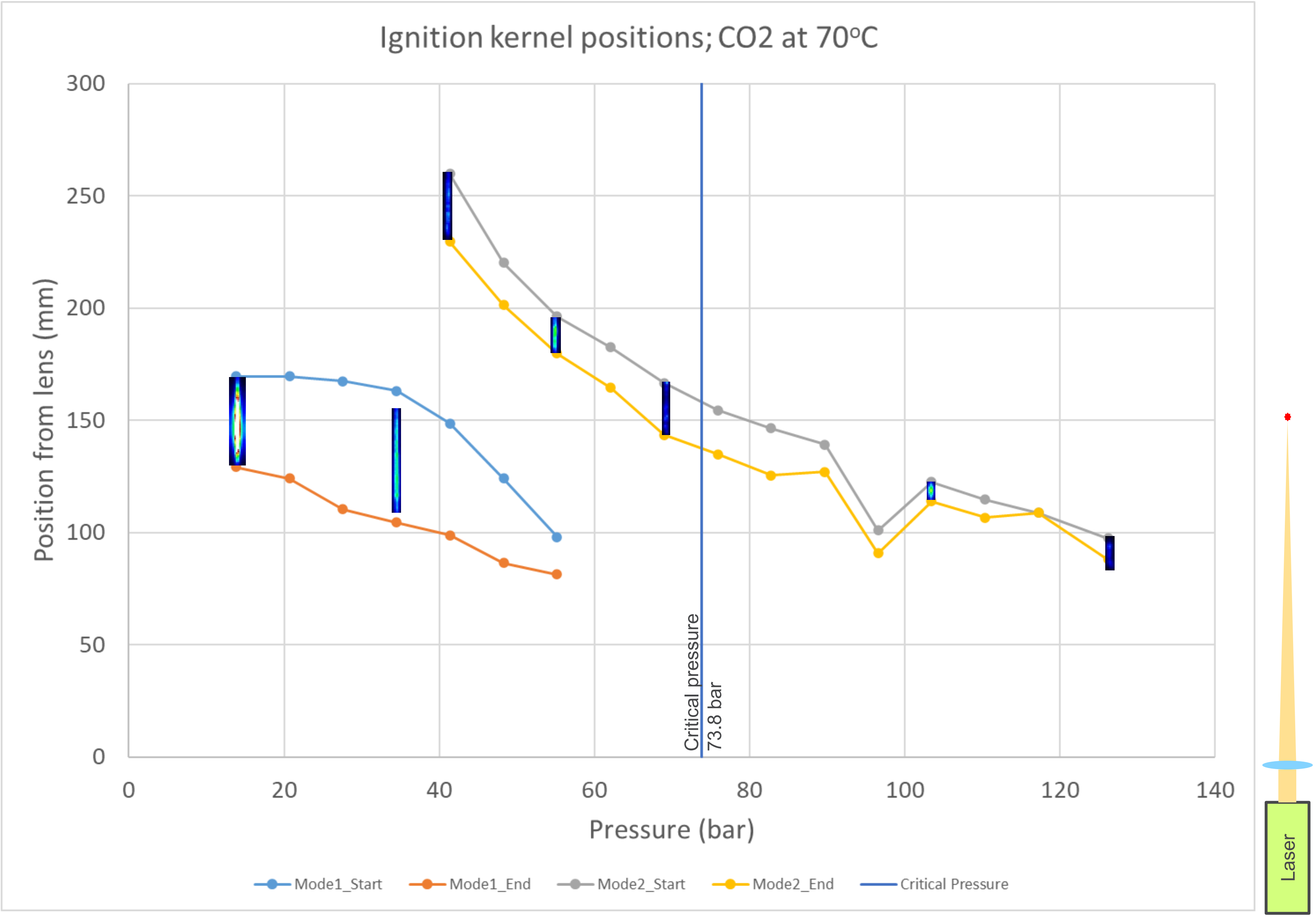
In $CO_2$

# Focal length = 150 mm; $CO_2$ at 70°C



# Focal length = 150 mm; $CO_2$ at 70°C




Ignition kernel positions; CO2 at 70°C
Position from lens (mm)
300
250
200
150
100
50
0
0
20
40
60
80
100
120
140
Pressure (bar)
Critical pressure
73.8 bar
Mode1_Start
Mode1_End
Mode2_Start
Mode2_End
Critical Pressure
Laser

# $CO_2$ BEHAVES AS A NON-LINEAR OPTICAL MEDIUM

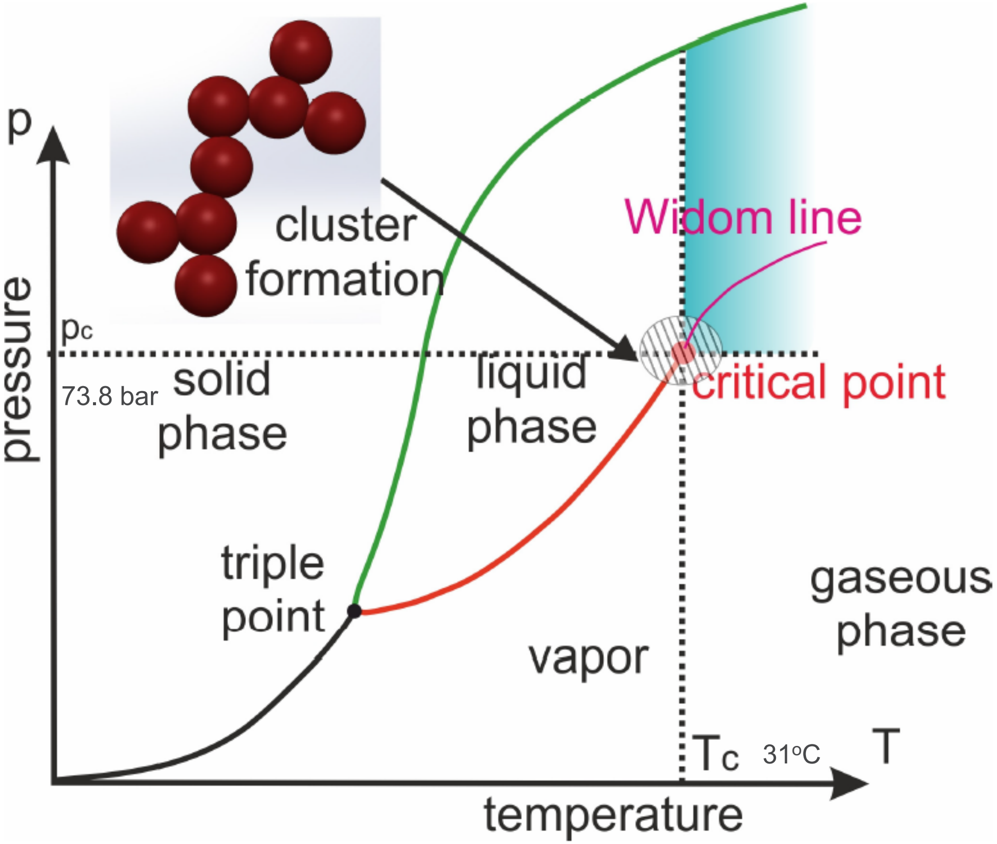
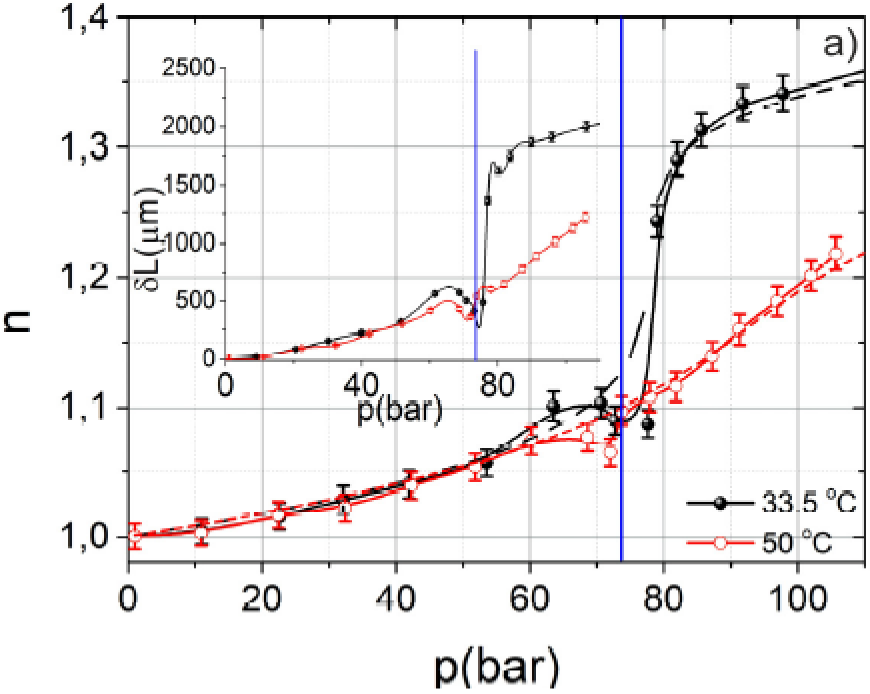


Fig. 2. The schematic phase diagram. The painted region refers to supercritical state of fluid. The region is divided by the Widom line into gas like SCF (under the Widom line) and liquid-like (over the Widom line). The maximum cluster formation is observed in the close vicinity of critical point [21]. The shaded region shows the area one the phase diagram, where strong scattering complicates the measurements.

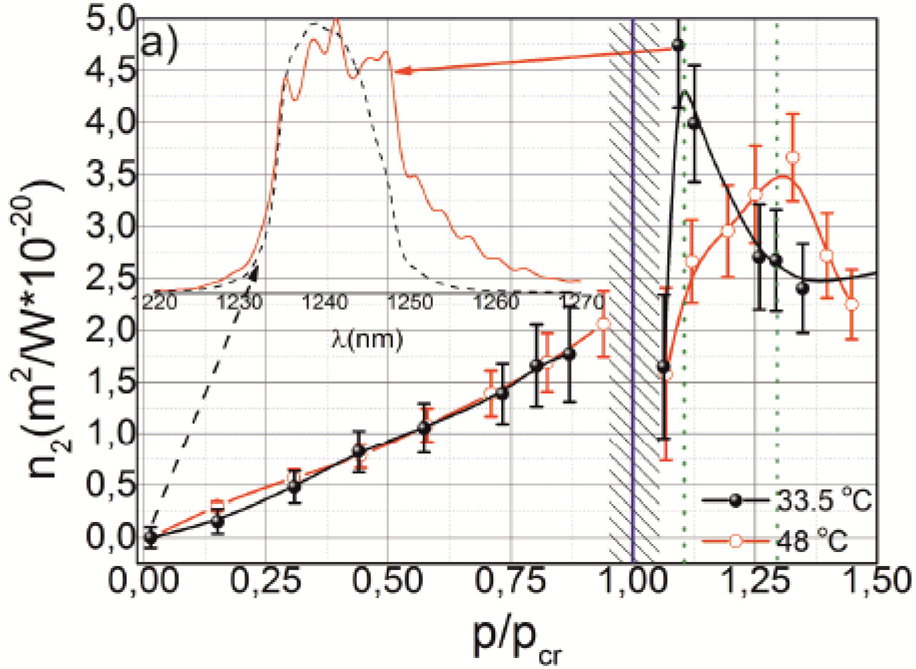
Mareev, E, et al.,
Vol. 26, No. 10 | 14 May 2018 | OPTICS EXPRESS 13232

$$n = n_o + \Delta n \cdot |E|^2$$

## Linear Refractive Index, $n_o$



## Non-linear Refractive Index, Δn



Mareev, E, et al., Vol. 26, No. 10 | 14 May 2018 | OPTICS EXPRESS 13232

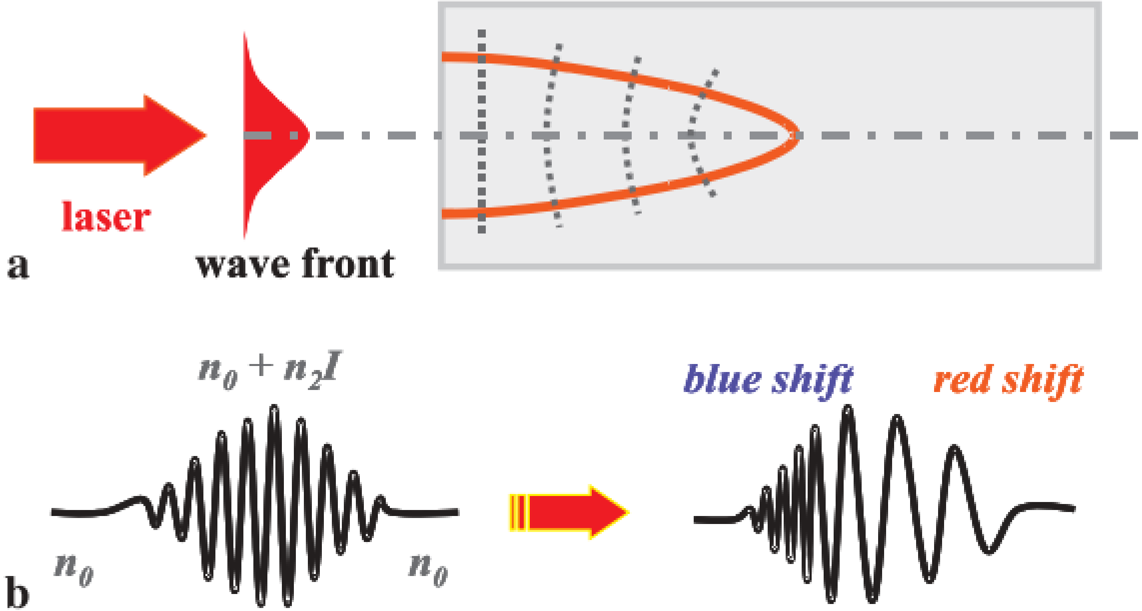
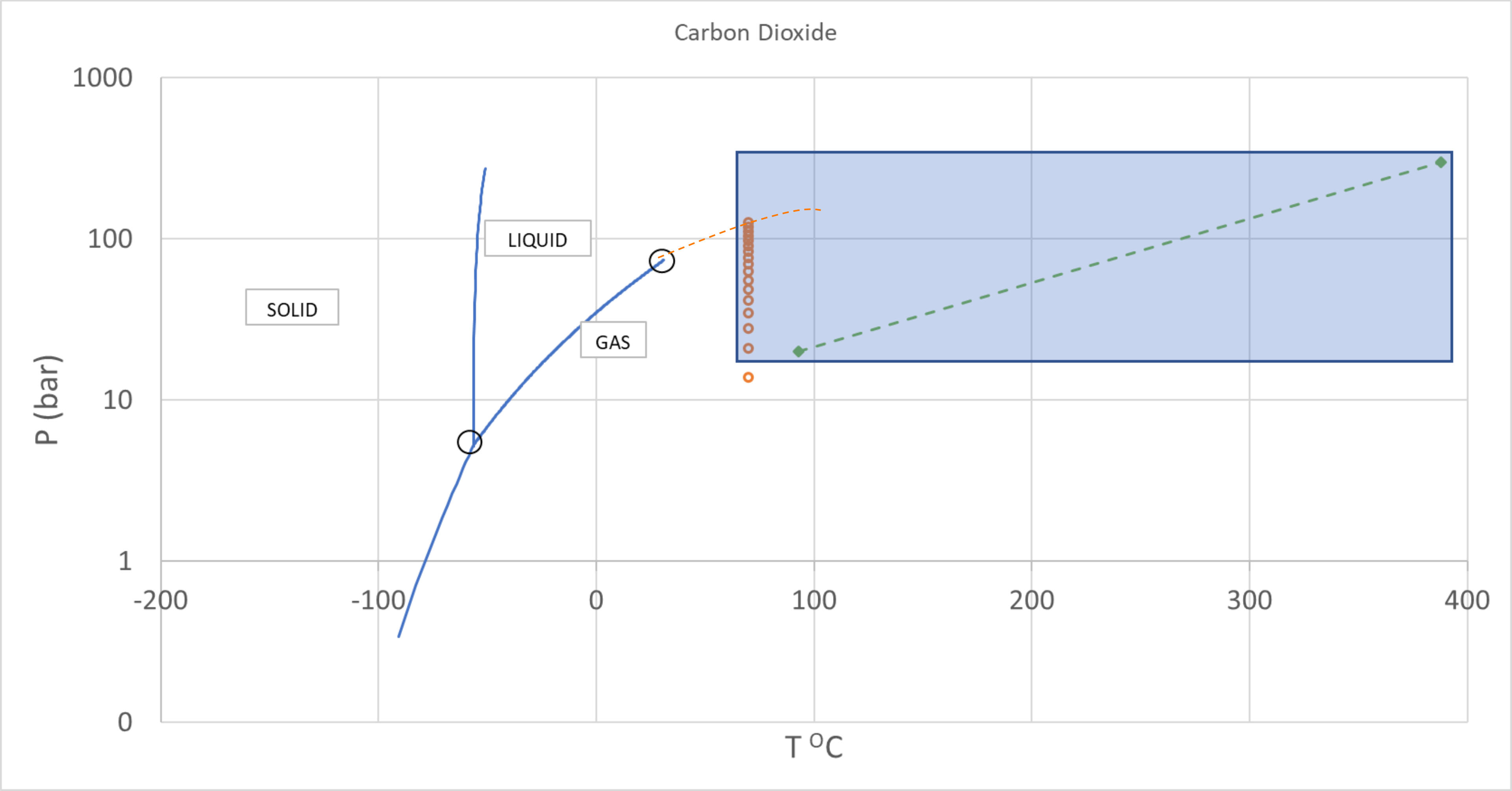


**FIGURE 3** Schematic illustration of **a** self-focusing and **b** self-phase modulation resulting from a nonlinear refractive index

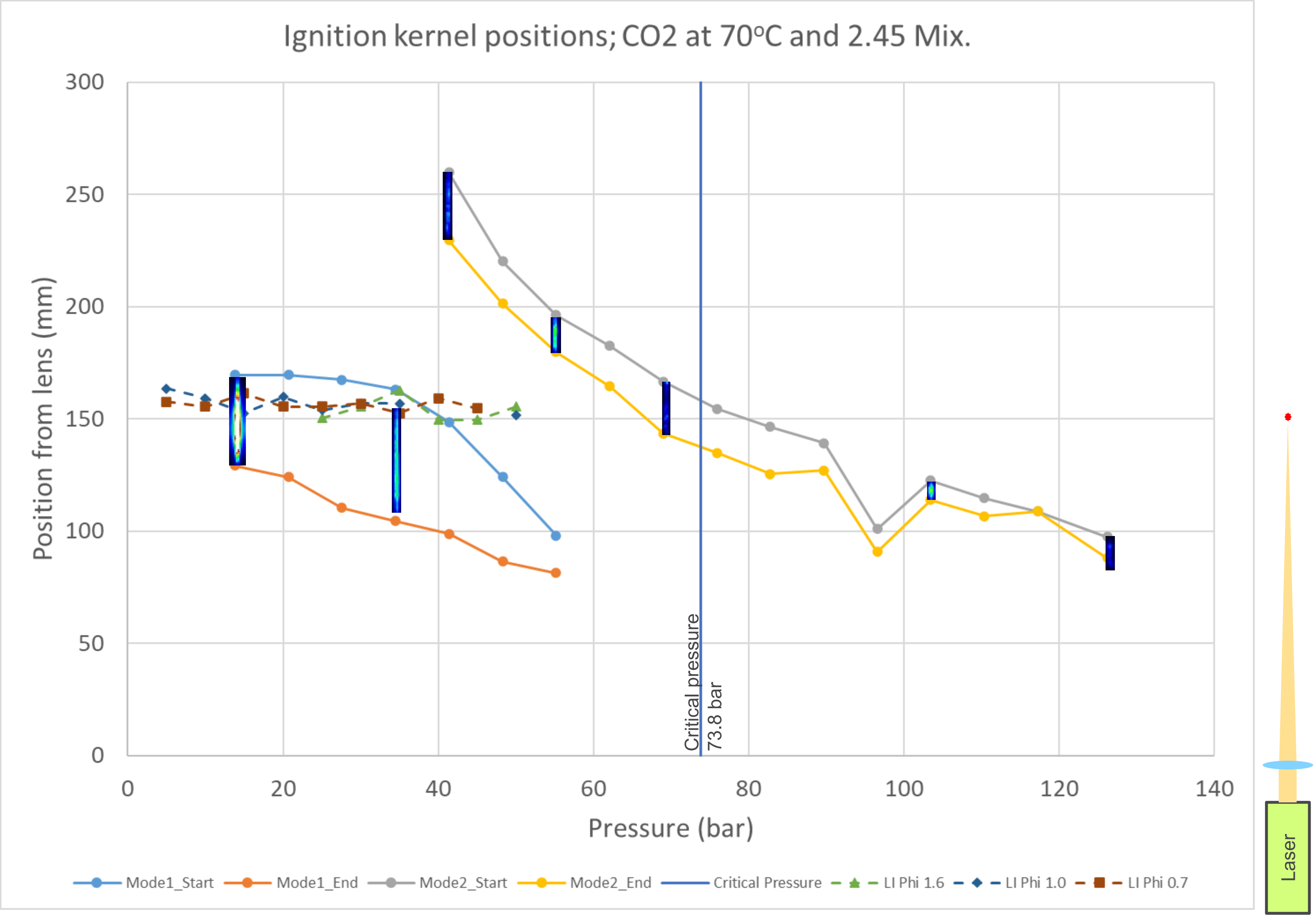
If Δn is positive, the central part of the beam having higher intensity should experience a larger refractive index than the edge and therefore should travel at a slower velocity than the edge.

Mao, S., Quéré, F., Guizard, S. *et al.* Dynamics of femtosecond laser interactions with dielectrics. *Appl Phys A* **79,** 1695–1709 (2004). https://doi.org/10.1007/s00339-004-2684-0



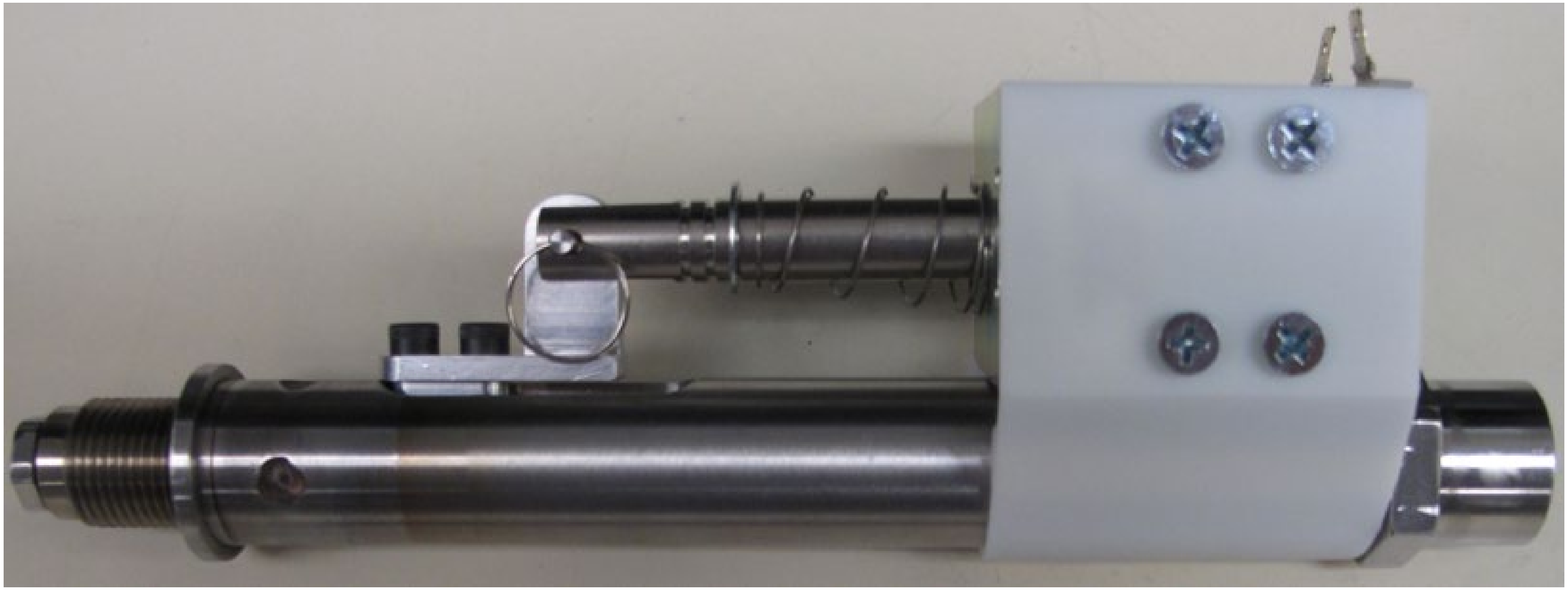
Q1: Is Widom line (orange dashed) a concern?
A1: No, projected ignition conditions (green dashed) are likely to stay away from Widom line.

Q2: Is CO2 optical non-linearity a concern?
A2: !!!

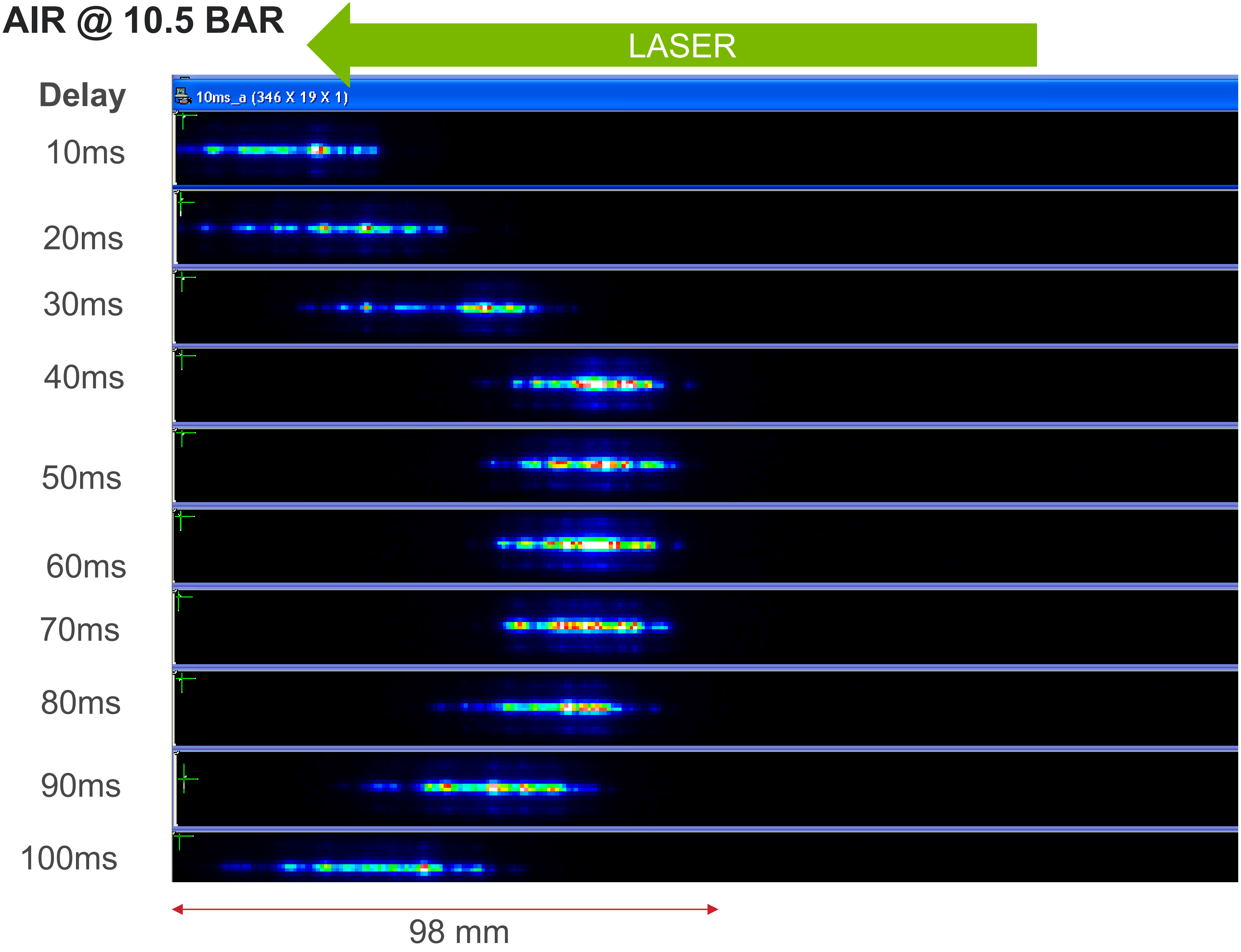

Ignition kernel positions; CO2 at 70ºC and 2.45 Mix.
Position from lens (mm)
300
250
200
150
100
50
0
0
20
40
60
80
100
120
140
Pressure (bar)
Critical pressure
73.8 bar
Mode1_Start
Mode1_End
Mode2_Start
Mode2_End
Critical Pressure
LI Phi 1.6
LI Phi 1.0
LI Phi 0.7
Laser

# VARI-FOCUS
# (VARIABLE FOCAL LENGTH IGNITER)

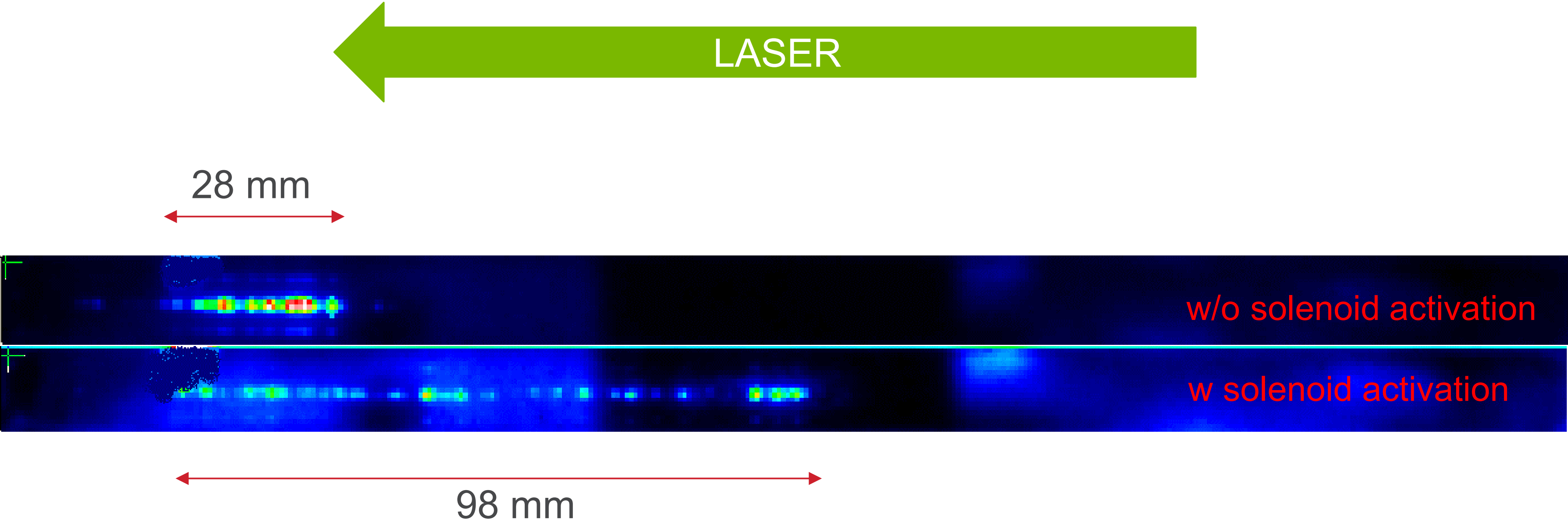
- WHEN IGNITION LOCATION IS NOT WELL DEFINED



# IN AIR @ 10.5 BAR



# 50 HZ LASER BURST, 7-PULSES



**In CO2 @ 21 bar** : non-linear effects are less pronounced

A 3.5X spatial spread in ignition kernels is evident

# SUMMARY

## Final Igniter Designs

- IGNITER#1: (FIXED FOCAL LENGTH) when flow fields are known a priori; like CFD evaluation
- IGNITER#2: (VARIABLE FOCAL LENGTH) when flow fields are not known ahead of time

## Lab-scale Igniter Evaluation

- **Igition kernel imaging.**: Multiple ignition kernels form at the focal point along the laser line of sight. Both volumetric ignition and use of multiple ignition pulses (i.e., burst mode ) significantly improve ignitability.

## Widom Line

- Not an issue - ignition conditions are largely removed from the Widom line

## Optical Non-linearity of $CO_2$

- Imaging in combustible mixtures show that it is not a concern

# THANK YOU!