航天动力领域导论

第三讲 先进燃烧诊断在航天动力中的应用

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提纲

一． 燃烧概述

二． 国外研究情况

三． 国内研究方法与进展

四． 对基础知识的需求

五． 总结

一、燃烧概述

虽然燃烧研究不够深入并不影响燃烧的使用，但是有时缺乏理解却成为严重的障碍。

Combustion is a complex phenomenon

Processes / Issues

Chemical kinetics

Flow processes

Physical processes
(*Diffusion, Heat conduction, Radiation*)

Thermodynamics

Different phases
(*Vapor, Droplets, Particles*)

Practical fuels

⇔

An example of combustion in a non-premixed flame

⇔

Tools

Experimental techniques

Theory and Modeling

What is combustion?

Combustion takes place in a flame characterized by:

- Exothermic reactions
  - Reactants $\rightarrow$ Products + Energy
- Oxidation processes
  - Oxygen in air is usually the oxidizer
- High temperatures of the products
  - Typically above 2000 K
- Radiation
  - Chemiluminiscence, Planck radiation

Combustion situations/applications

For specified tasks

Candle light
Welding flame
Bunsen burner
Log fire
Liquid gas stove

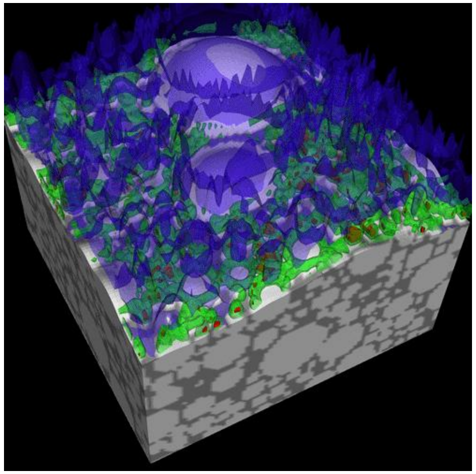
For efficiency and low emissions

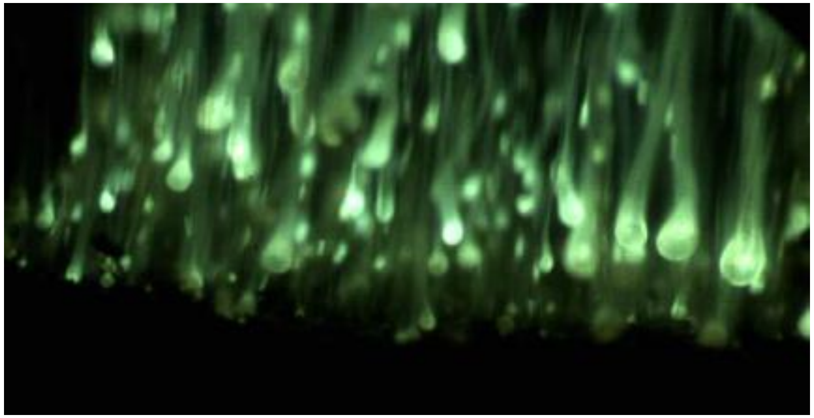
Furnace
Fluidized bed
Diesel engine
Gasoline engine
$\boxed{\text{Rocket engine} \\ \text{Jet engine}}$
Gas turbine

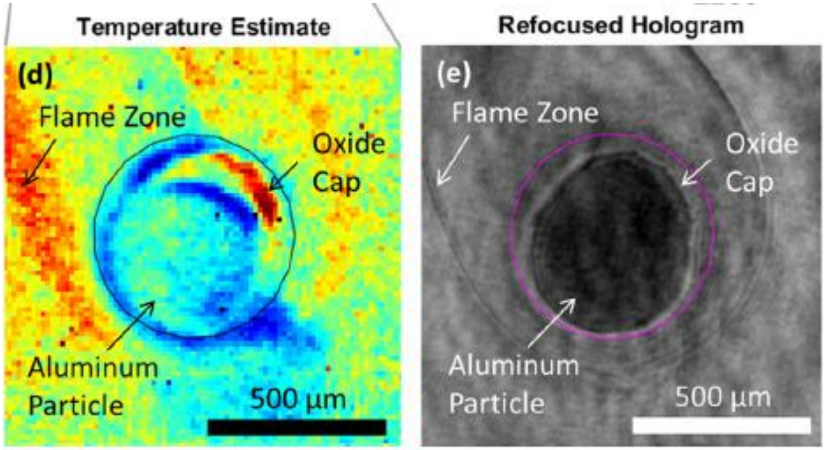
Unwanted events

Fire
Explosion
Detonation

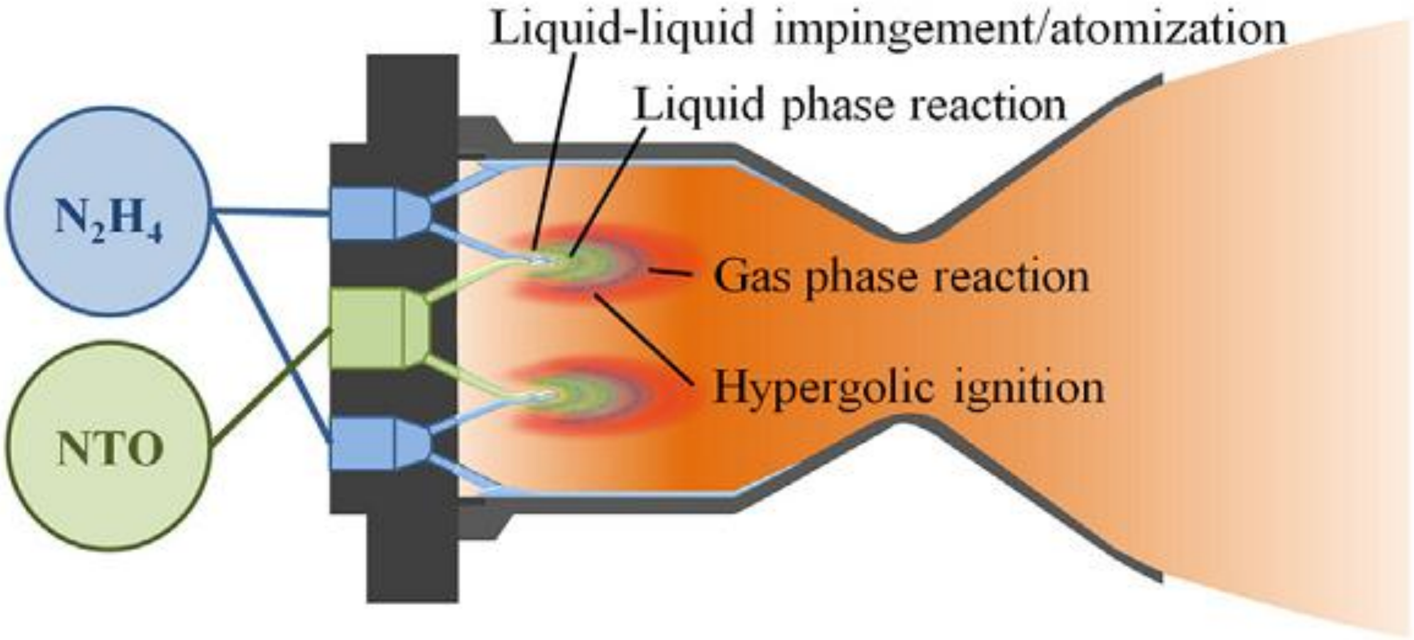
固体火箭发动机





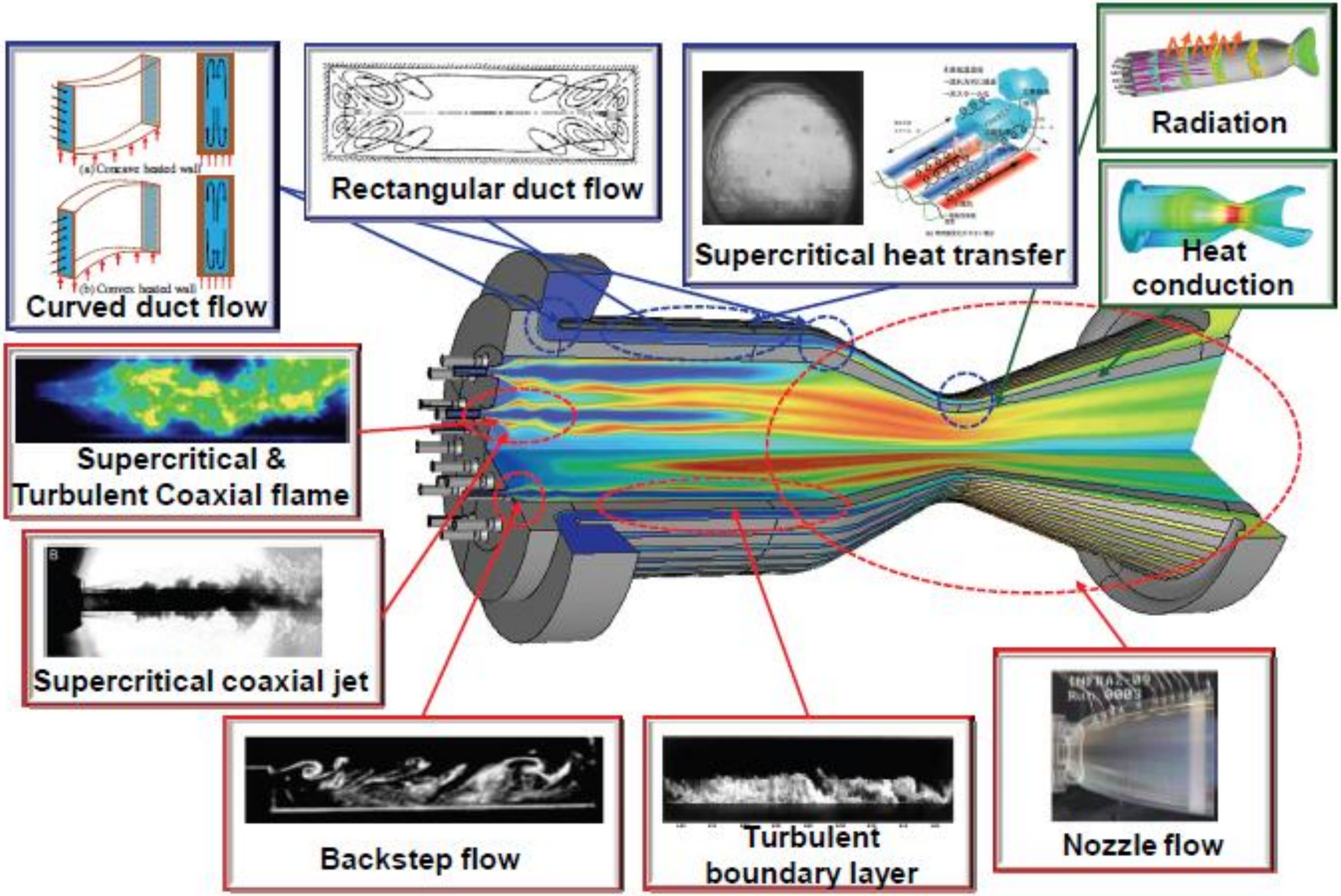

Temperature Estimate
(d)
Flame Zone
Oxide
Cap
Aluminum
Particle
500 µm
Refocused Hologram
(e)
Flame Zone
Oxide
Cap
Aluminum
Particle
500 µm

液体火箭发动机



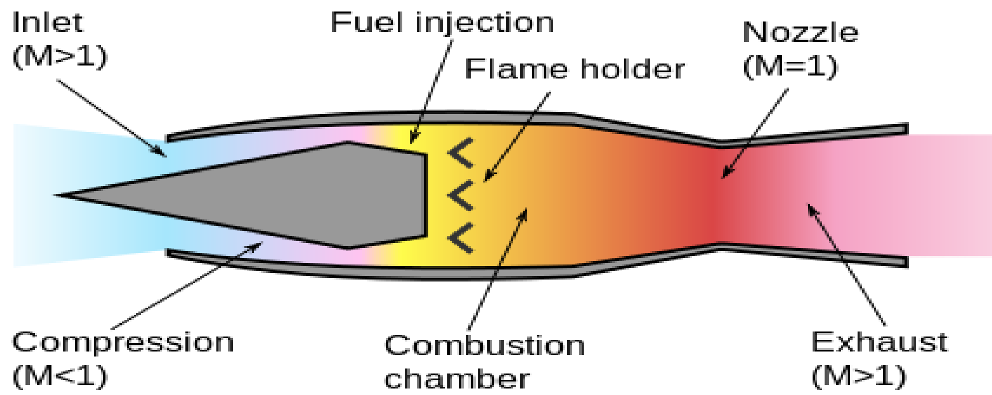
Liquid-liquid impingement/atomization
Liquid phase reaction
N_2H_4
Gas phase reaction
Hypergolic ignition
NTO

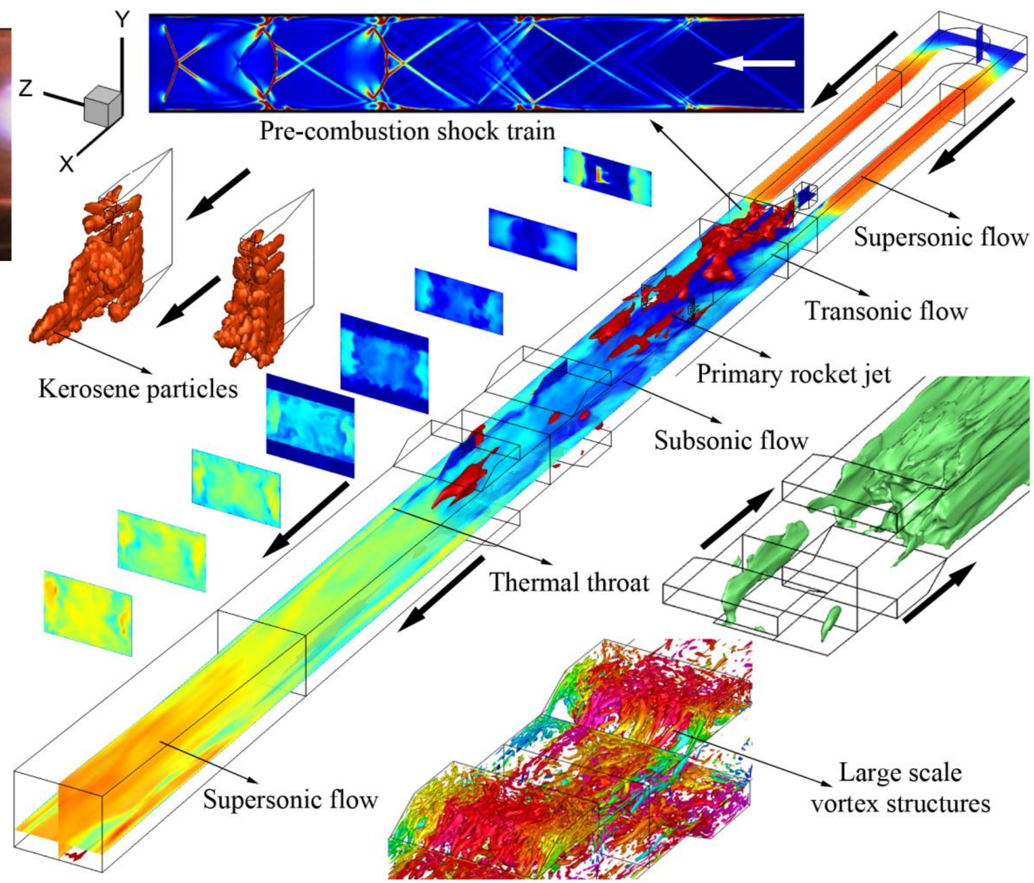
液体火箭发动机



Curved duct flow
(a) Concave heated wall
(b) Convex heated wall
Rectangular duct flow
Supercritical heat transfer
Radiation
Heat conduction
Supercritical & Turbulent Coaxial flame
Supercritical coaxial jet
Backstep flow
Turbulent boundary layer
Nozzle flow

火箭冲压发动机


Inlet
(M>1)
Fuel injection
Flame holder
Nozzle
(M=1)
Compression
(M<1)
Combustion
chamber
Exhaust
(M>1)


Y
Z
X
Pre-combustion shock train
Kerosene particles
Supersonic flow
Transonic flow
Primary rocket jet
Subsonic flow
Thermal throat
Supersonic flow
Large scale
vortex structures

二、燃烧诊断的目的、能力及限制

Motivation for combustion research

By an improved fundamental understanding of combustion processes there will be a potential to

- improve efficiency

  lower fuel consumption ($\Rightarrow$ less CO_2)

- reduce emissions

  NO_x, SO_x, particles

LPF, Flameless combustion

- develop combustion of alternative fuels and new technology

  hydrogen combustion, fuel cells

- improve safety

  suppress fire initiation and spread

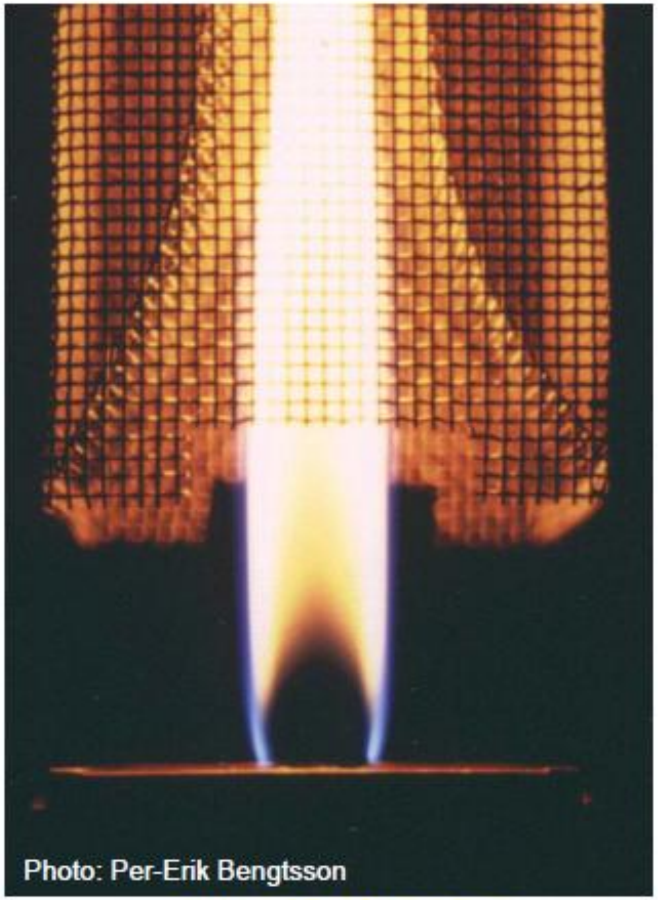
What should be measured?

Parameters

Concentrations of species
Temperature
Velocities
Particles (sizes, concentrations, volume fractions)
Droplets (sizes, concentrations, volume fractions)
Fuel/air ratios
Pressures

Demands

Presence of species
Qualitative/Quantitative
Temporal resolution
Spatial resolution (point, 1-D, 2-D, 3-D)
Accuracy
Precision

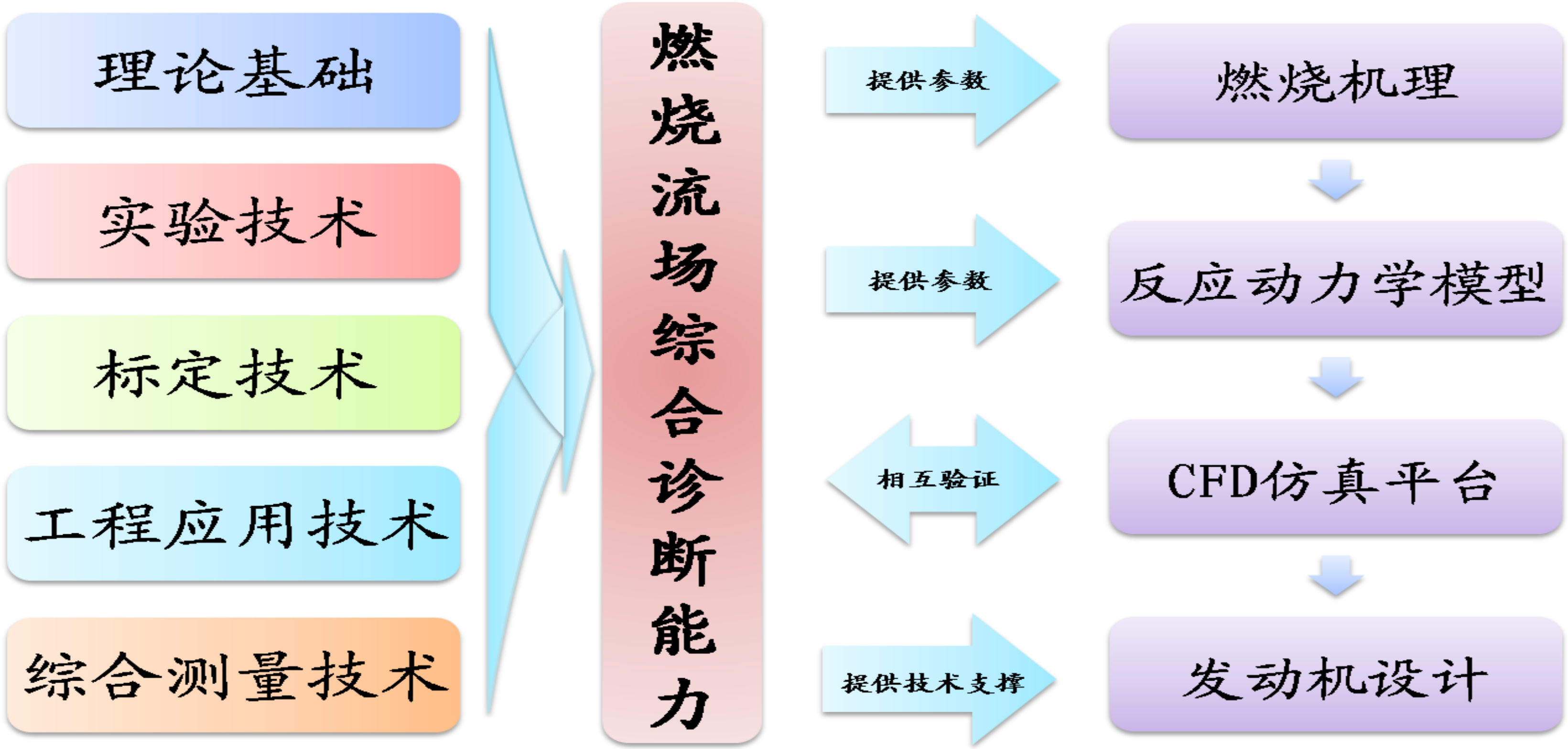


Diffusion flame on Wolfhard-Parker burner

提出明确的测试需求是完成测试的第一步！
不同的对象对测量精度的需求差别较大！

Perturbations in probe measurements

- Aerodynamic effects
  - The flow field is perturbed close to the probe
- Affects concentration gradients
- Thermal effects
  - A probe possesses heat losses to the flame
- Catalytic effects
- Quenching effects



形成燃烧基础科学研究、高保真CFD仿真、发动机高精度试验验证为一体的燃烧室预测设计方法。

Non-intrusive
A probe disturbs the combustion

High spatial resolution
Diam. 100 μm, length 100 μm

High temporal resolution
Pulse duration: 10 ns

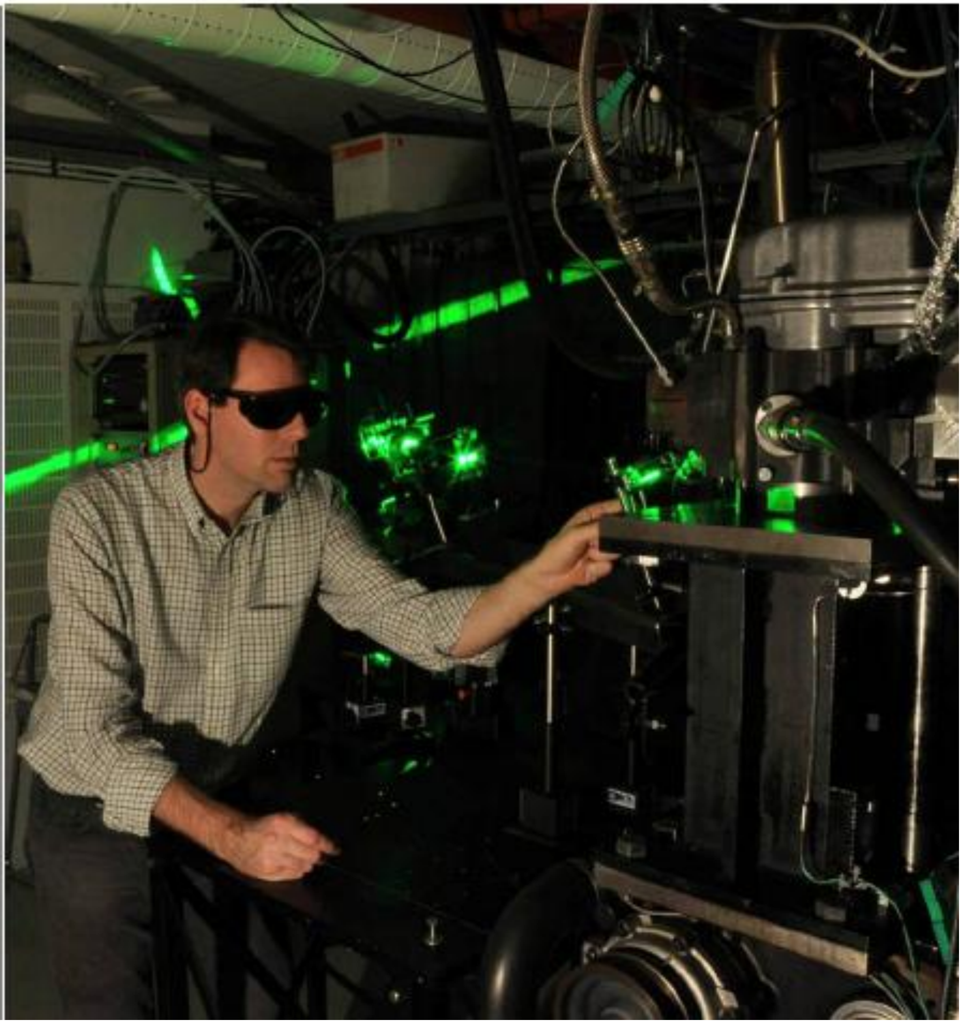
Species specific
Absorption at specific wavelength
Signal at specific wavelength

In-situ measurements
Measurements are performed where the combustion occurs.

Remote measurements

No upper temperature limit

Non-equilibrium can be probed



What could limit us?

- Noise in laser radiation
- Detection noise
- Averaging of information from measurements
- Laser-induced disturbances
- Background emission from flame
- Lack of molecular data
- Insufficient theoretical models
- Detection limit

Do not use a laser diagnostic technique unless you really have to use it.

Limitations of laser diagnostic techniques

Optical access is needed

Line-of-sight access

Line-of-sight access + orthogonal window

Complex experiments

Operator skill is needed

Interpretation may be advanced

Limited number of species

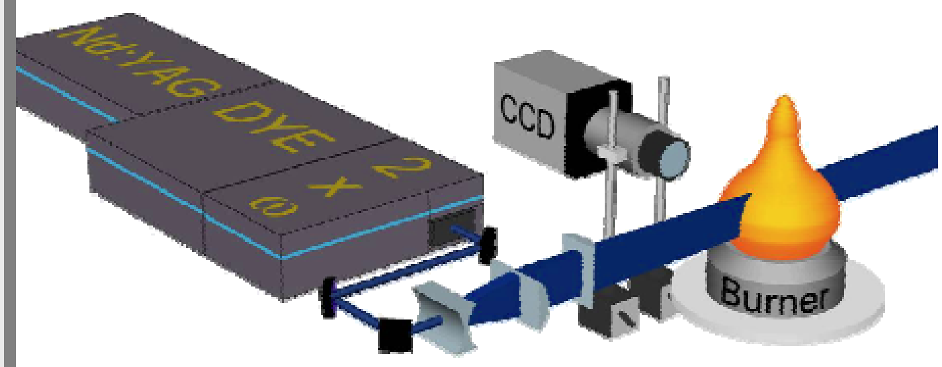
A given set-up may be used for a few species

Best for small molecules

Spectra specific for few-atom molecules only

High cost

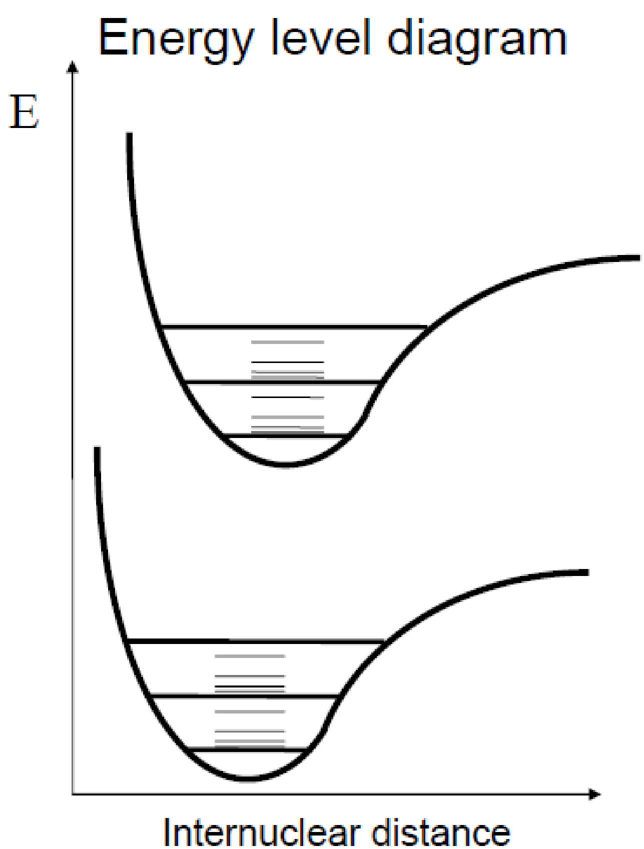
Should be used only when simpler methods give too limited information

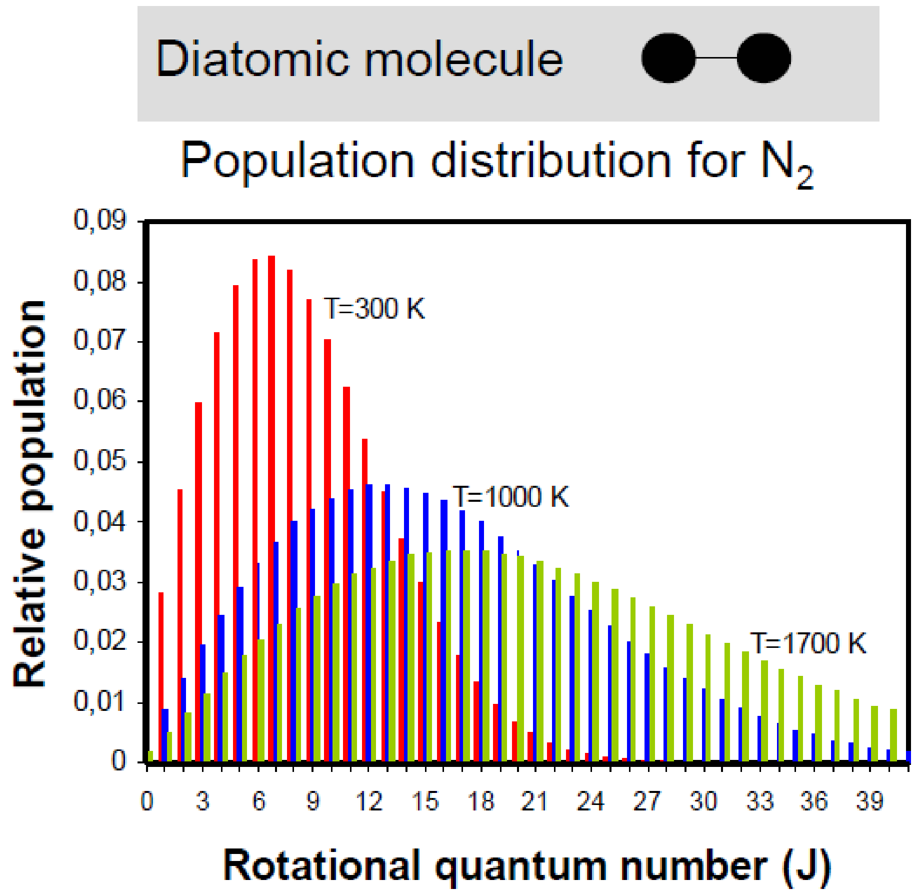


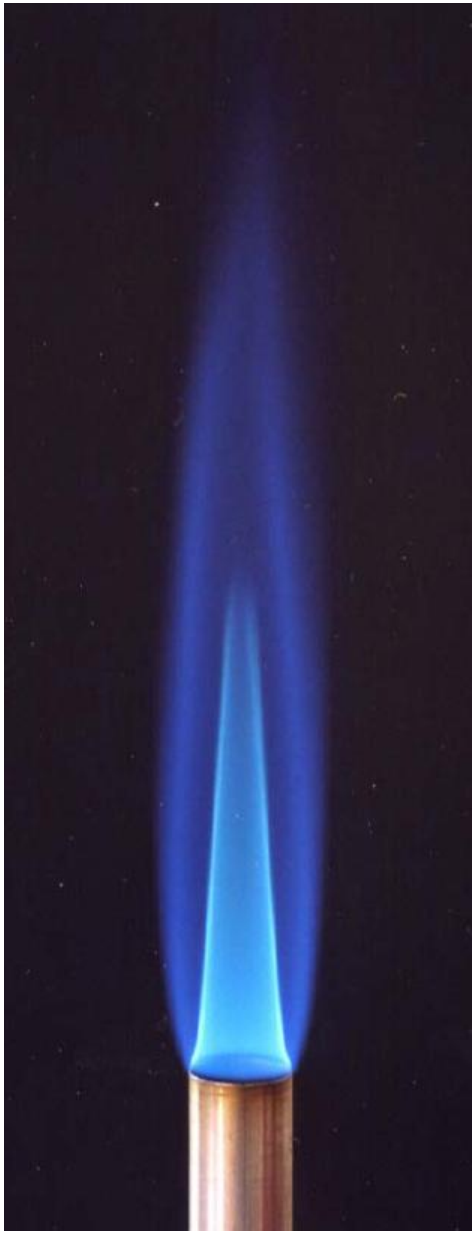
Typical experimental setup for 2D PLIF

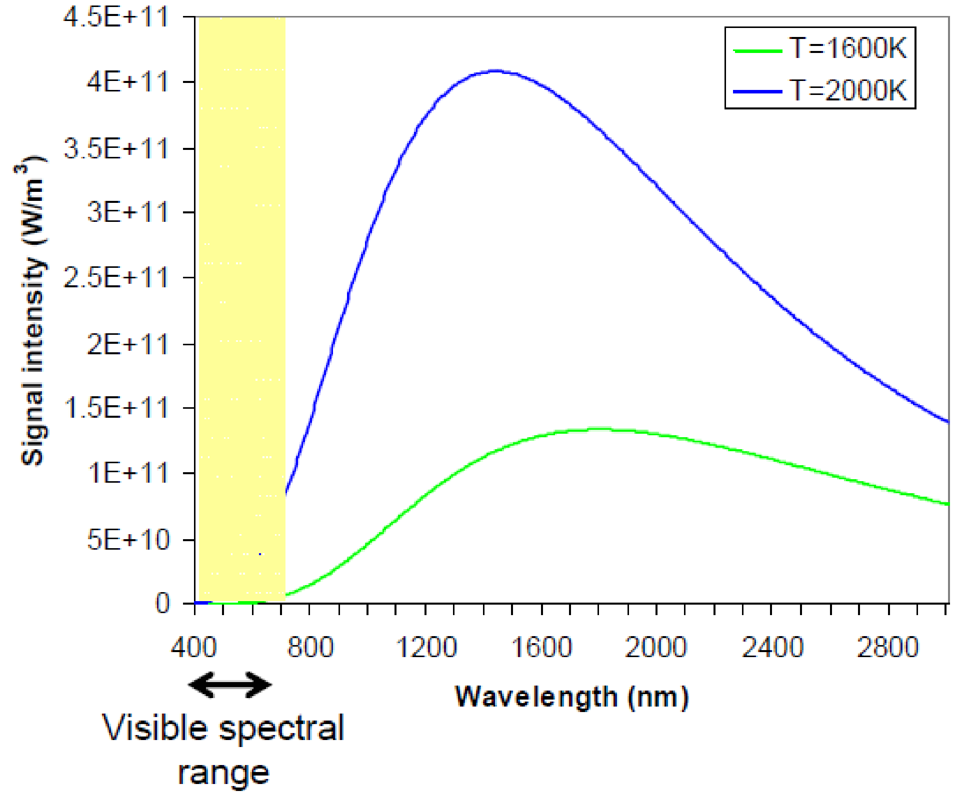
三、先进燃烧诊断技术

如何从火焰中获得想要的数据？温度、成份、浓度等





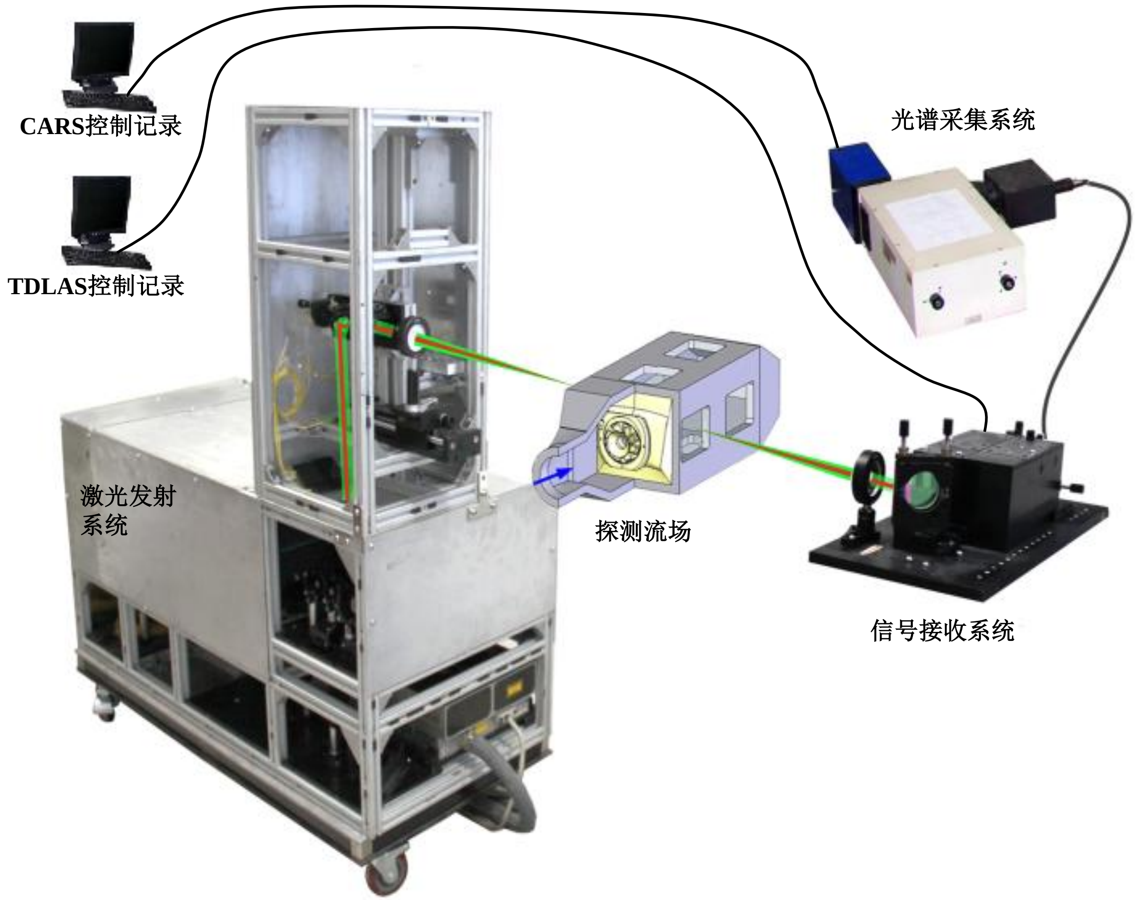


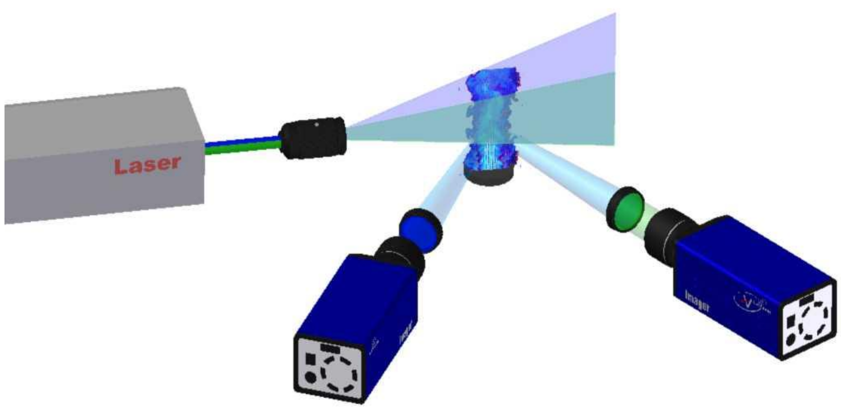


光与物质相互作用：

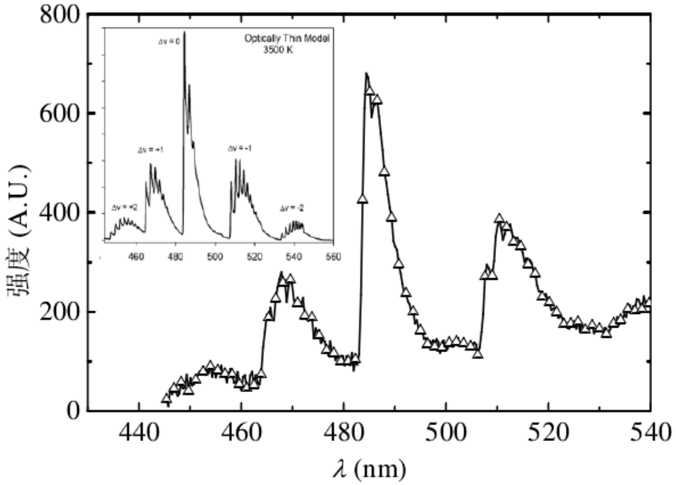
吸收、折射、散射、荧光、磷光等。

- 激光源
- 光路系统
- 信号探测系统
- 采集控制系统
- 光谱数据分析软件

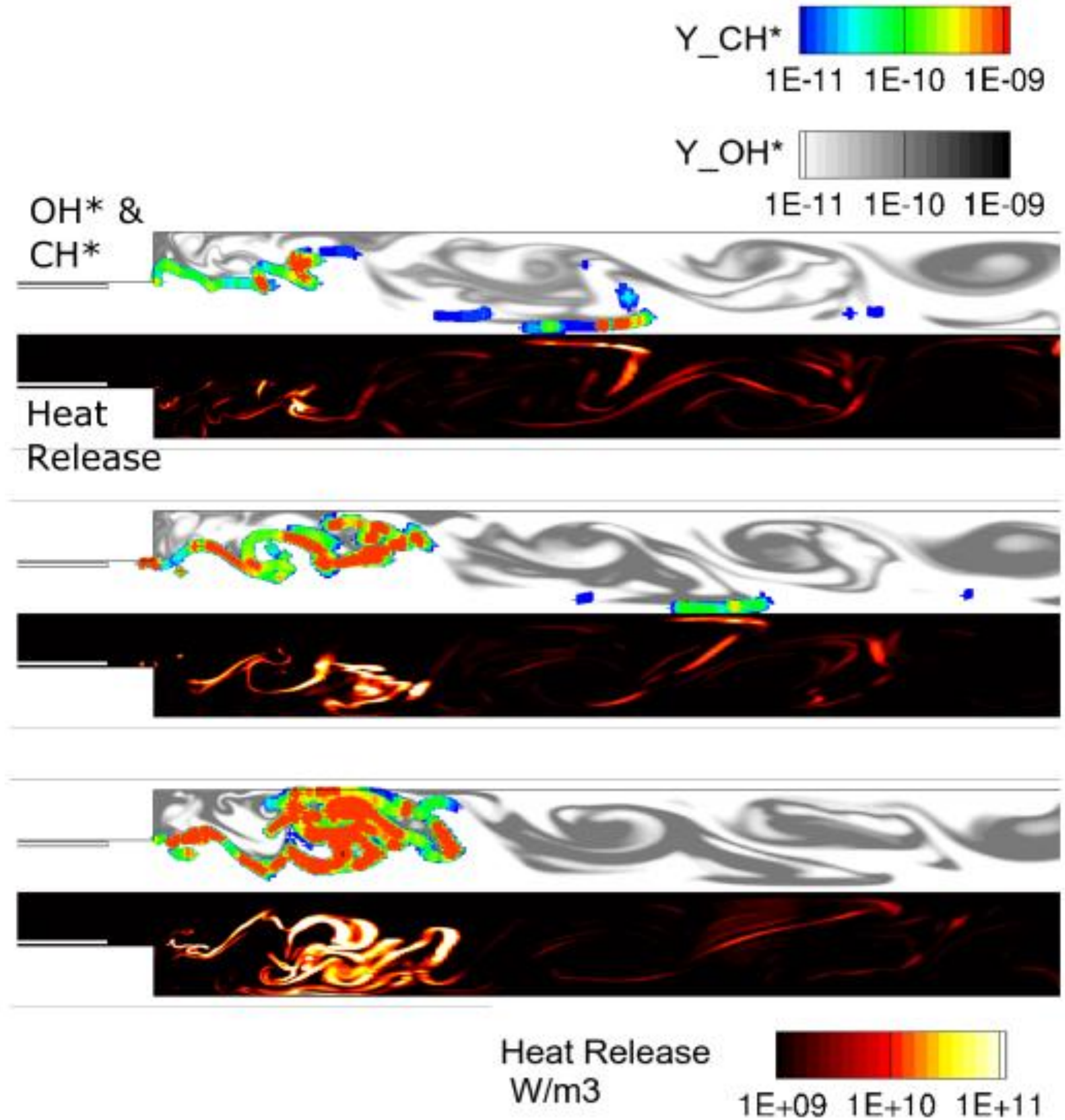




化学发光法

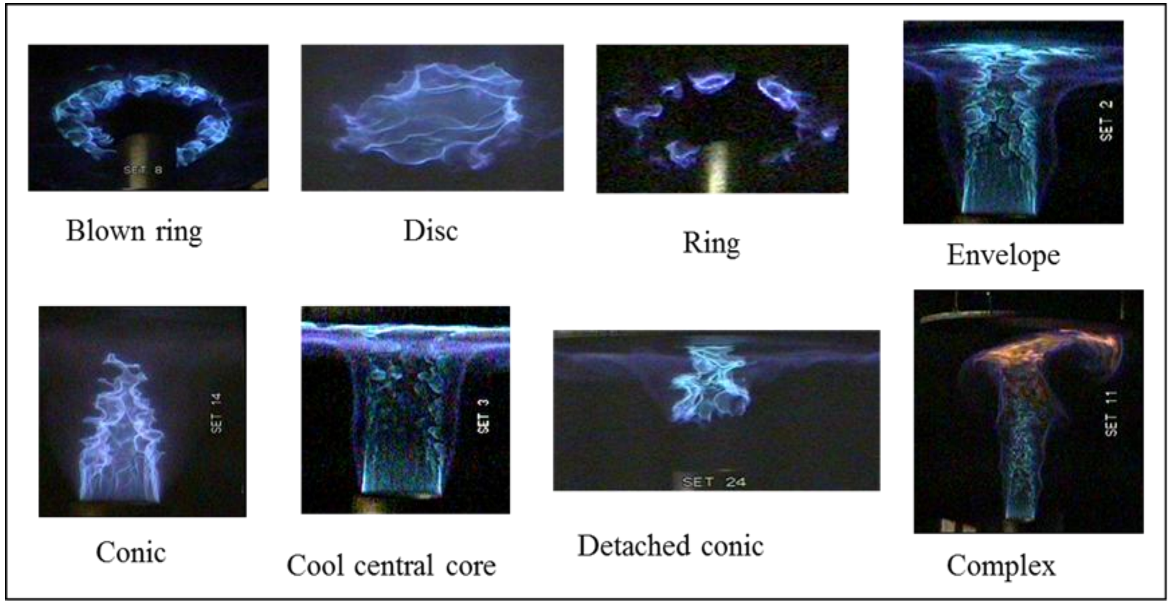


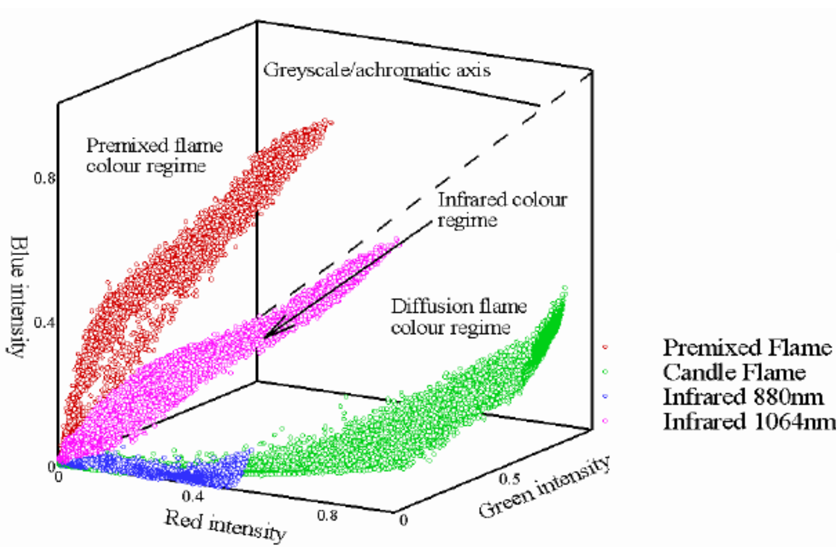
800
600
400
200
0
强度 (A.U.)
440 460 480 500 520 540
λ (nm)
Optically Thin Model
3500 K

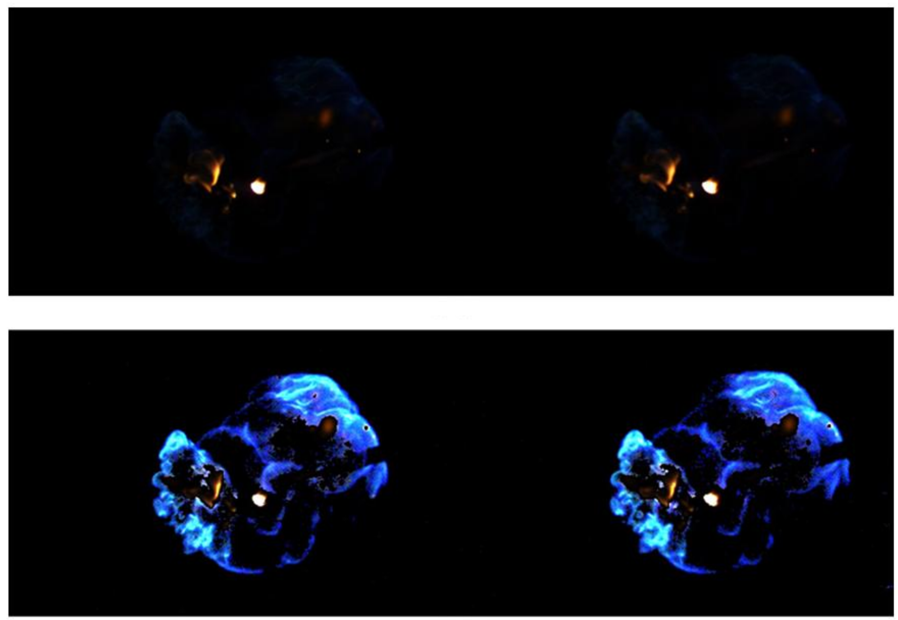


Y_CH*
1E-11 1E-10 1E-09
Y_OH*
1E-11 1E-10 1E-09
OH* &
CH*
Heat
Release
Heat Release
W/m3
1E+09 1E+10 1E+11

化学发光法

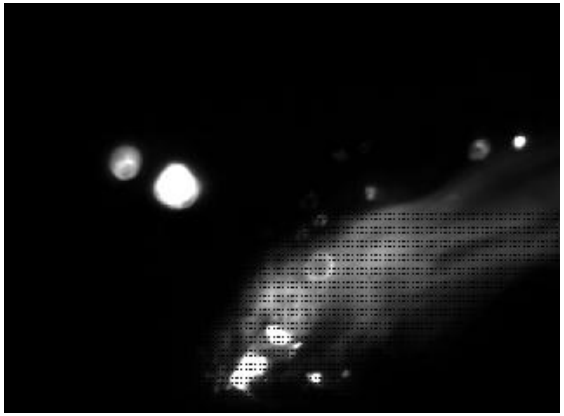




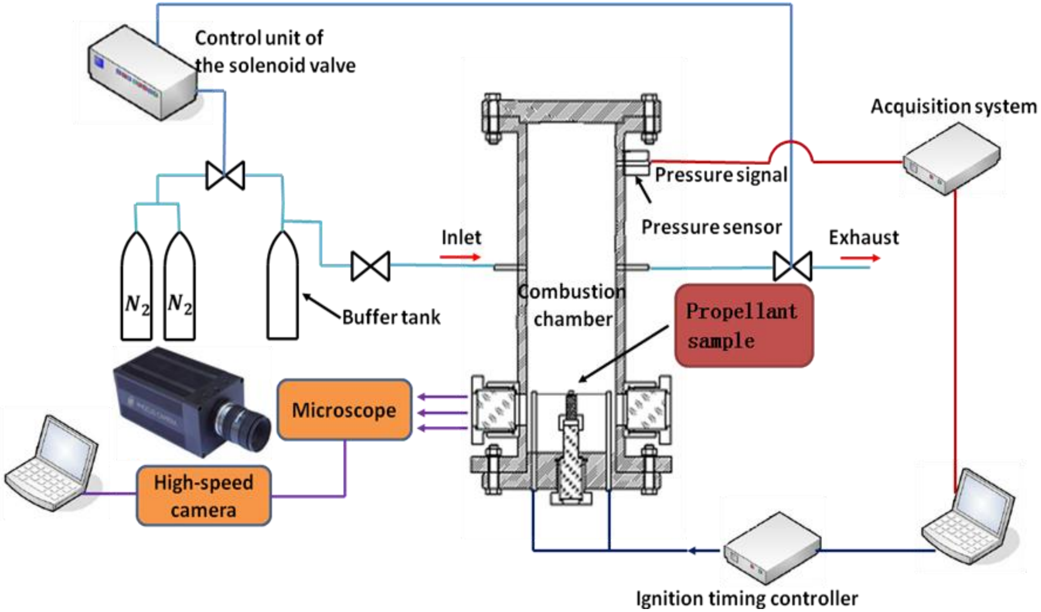


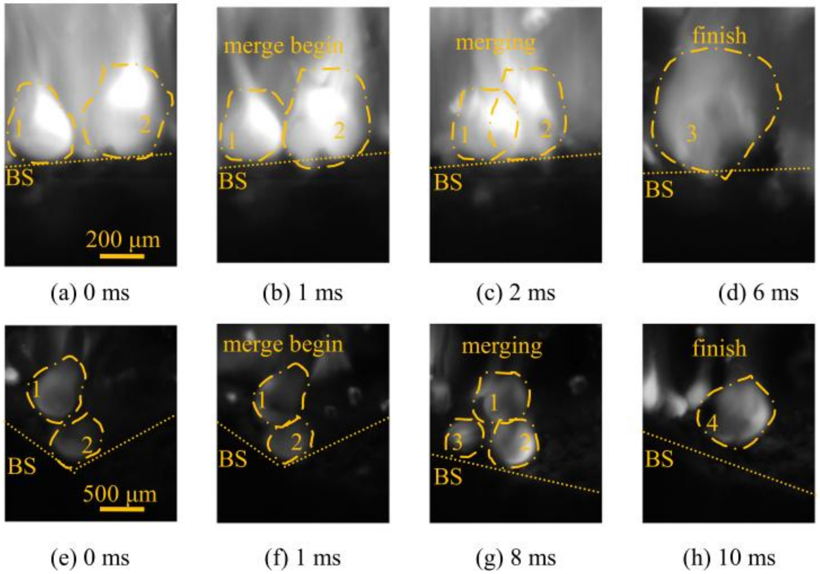
原始照片和蓝色增强后的照片

细观燃烧实验研究方法：长焦显微



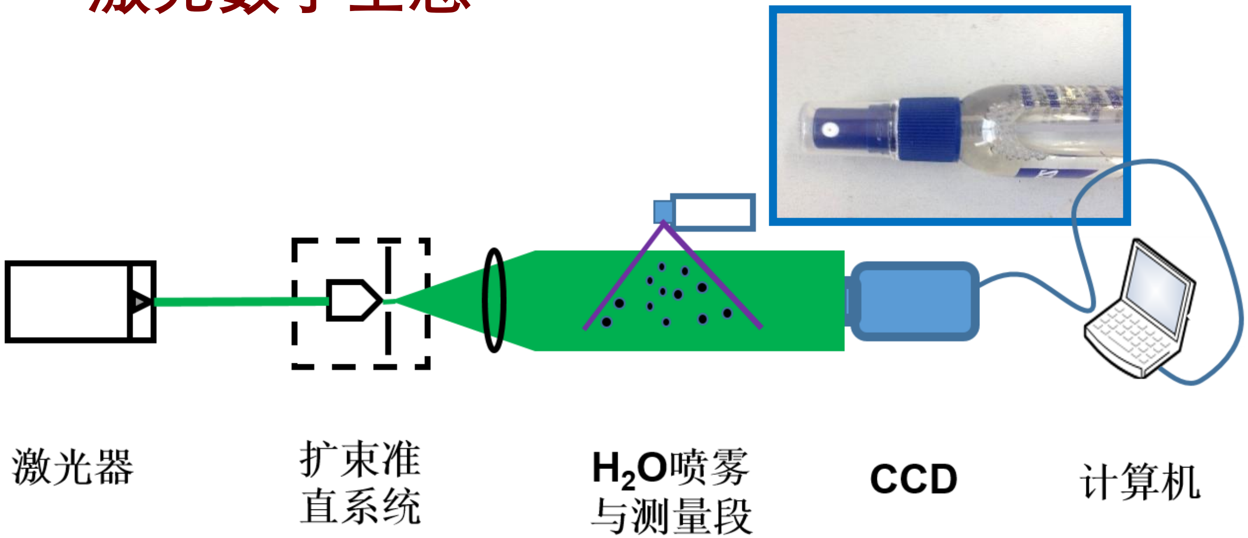
速度脉动条件下的火焰



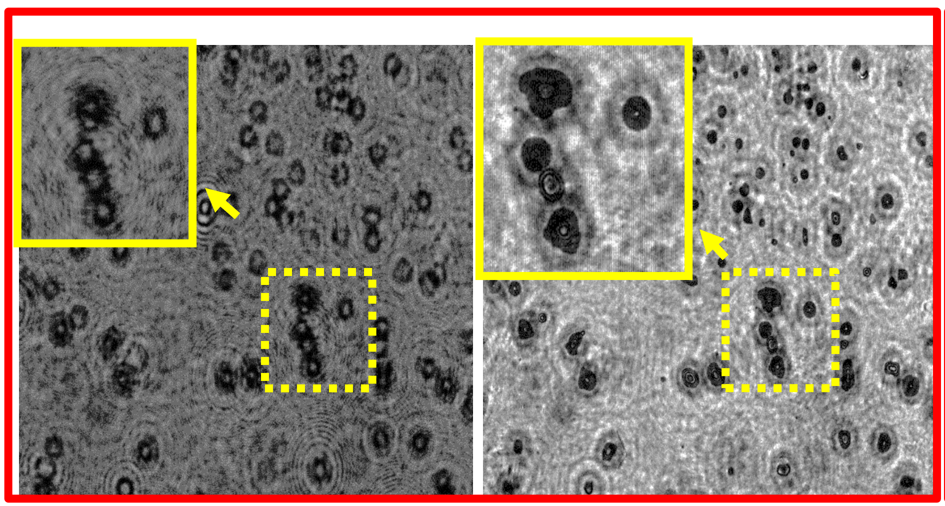


铝在推进剂表面的聚集

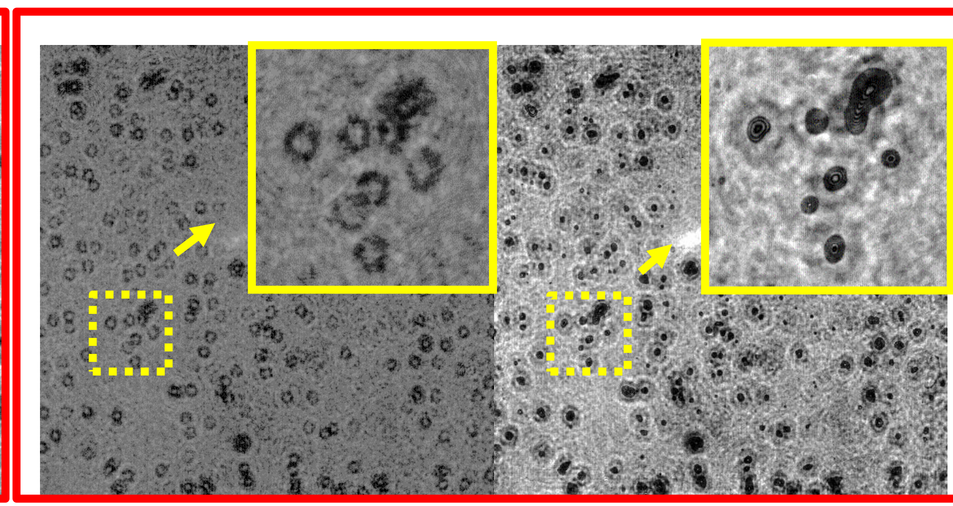
激光数字全息



增加H_2O喷雾装置获得喷雾场全息图像。



喷雾全息图像 → 喷雾聚焦图像



喷雾全息图像 → 喷雾聚焦图像

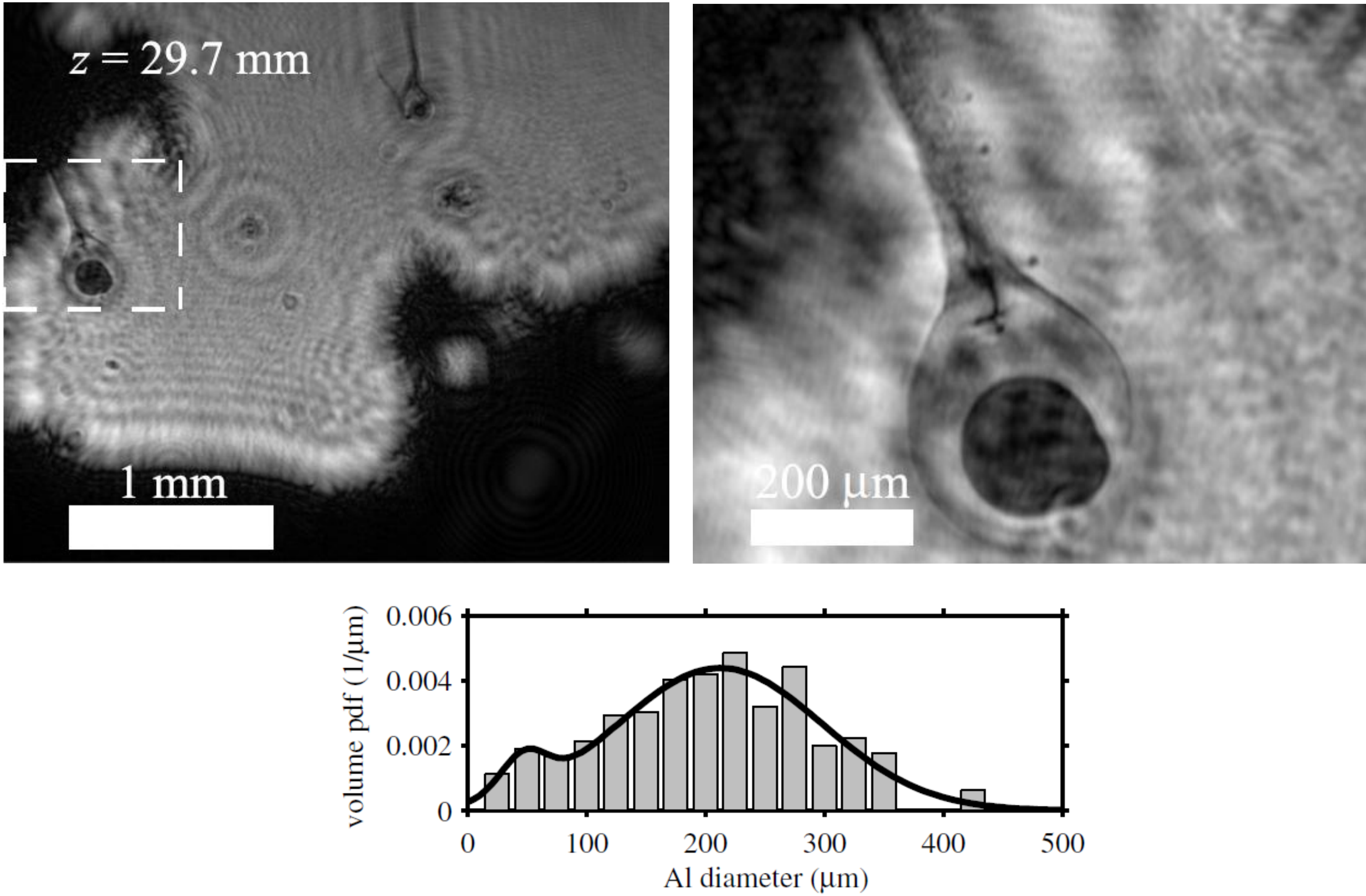
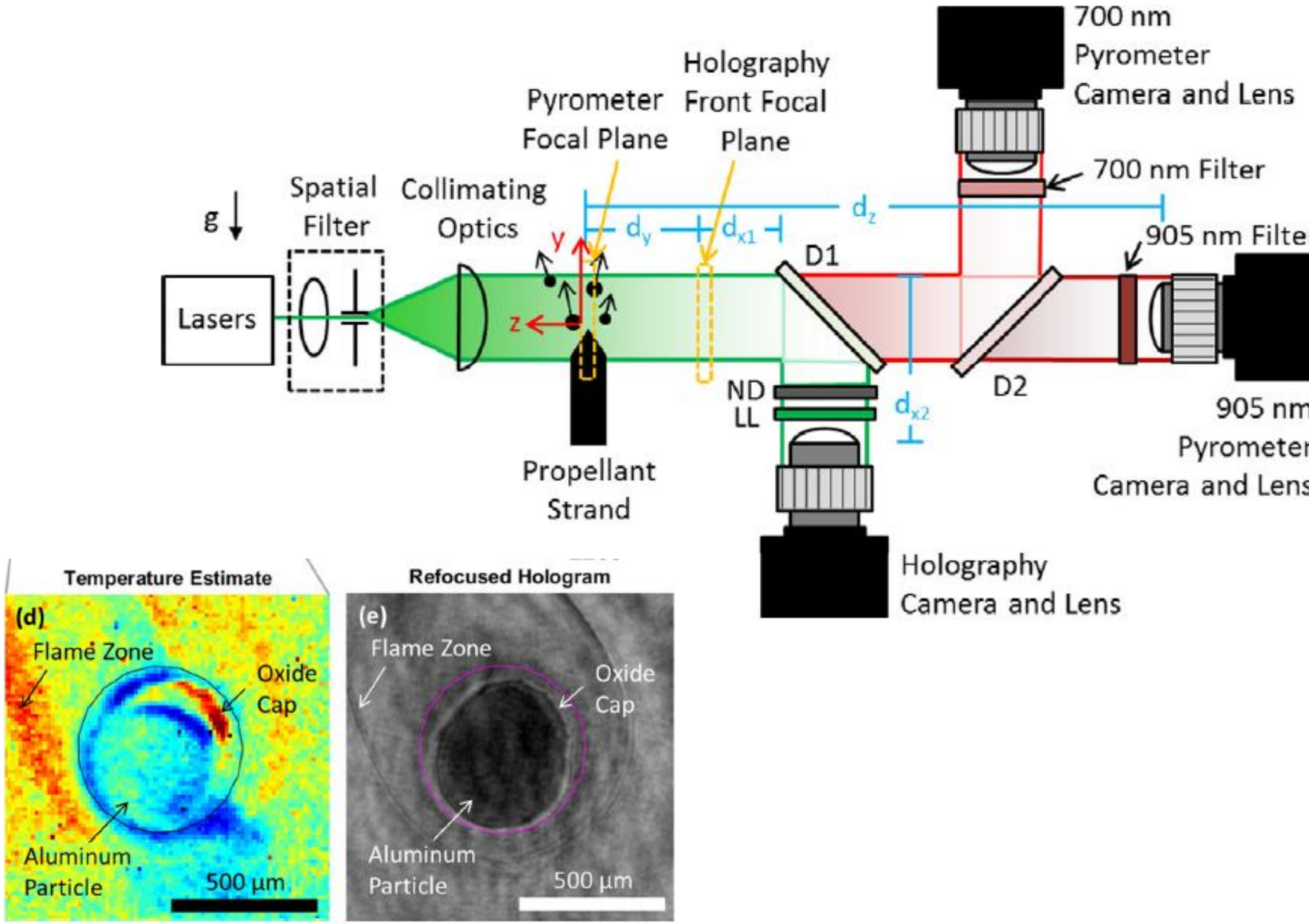


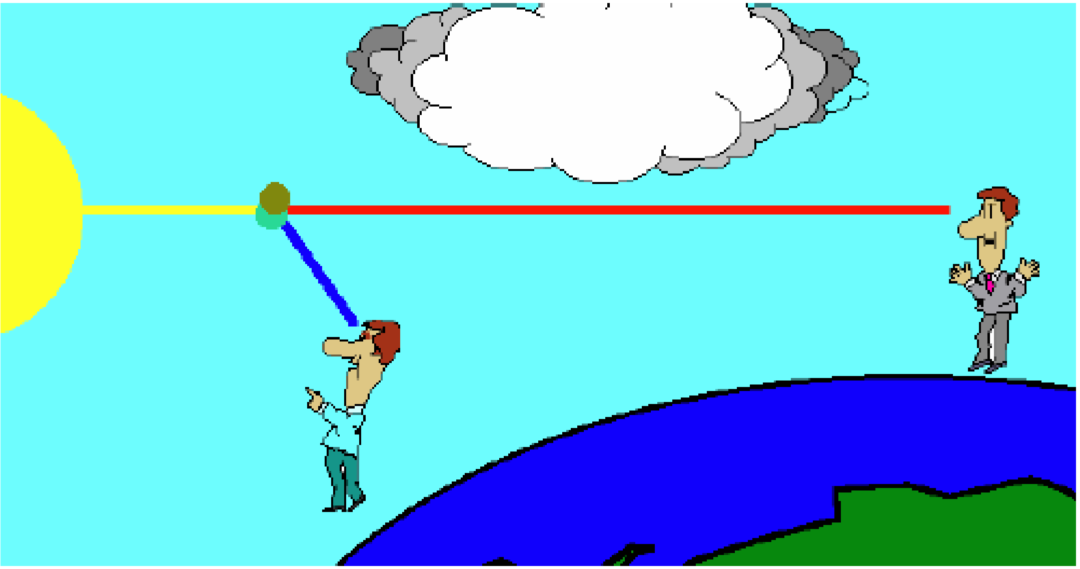
Fig. 6. Volumetric size distribution measured with DIH (gray bars). The solid line shows the best fit two-component Gaussian mixture model.



700 nm
Pyrometer
Camera and Lens
Holography
Front Focal
Plane
Pyrometer
Focal Plane
700 nm Filter
Spatial
Filter
Collimating
Optics
d_z
g
d_y
d_{x1}
905 nm Filter
y
D1
Lasers
z
ND
LL
D2
d_{x2}
905 nm
Pyrometer
Camera and Lens
Propellant
Strand
Holography
Camera and Lens
Temperature Estimate
Refocused Hologram
(d)
Flame Zone
Oxide
Cap
Aluminum
Particle
500 µm
(e)
Flame Zone
Oxide
Cap
Aluminum
Particle
500 µm

散射

Why is the sky blue?



- Daytime sky looks blue on a clear day
- The sky looks red at sunrise and sunset

Why?

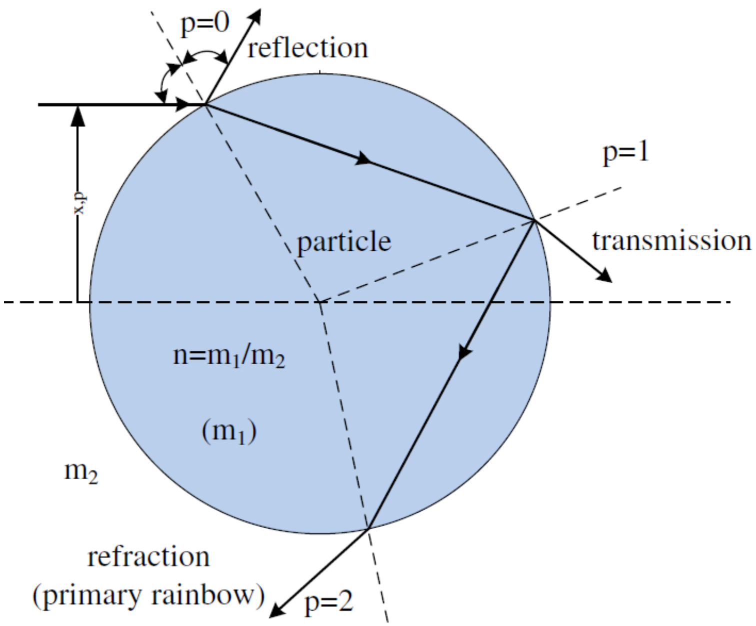
Blue light is scattered more efficiently than red

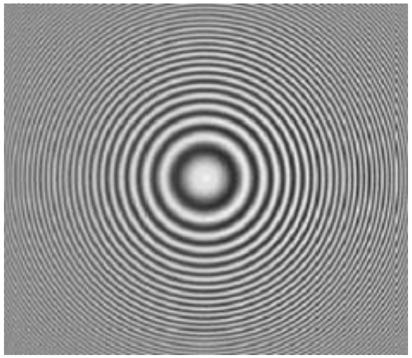
Elastic scattering ($\lambda_{\text{scattered light}} = \lambda_{\text{incoming light}}$)

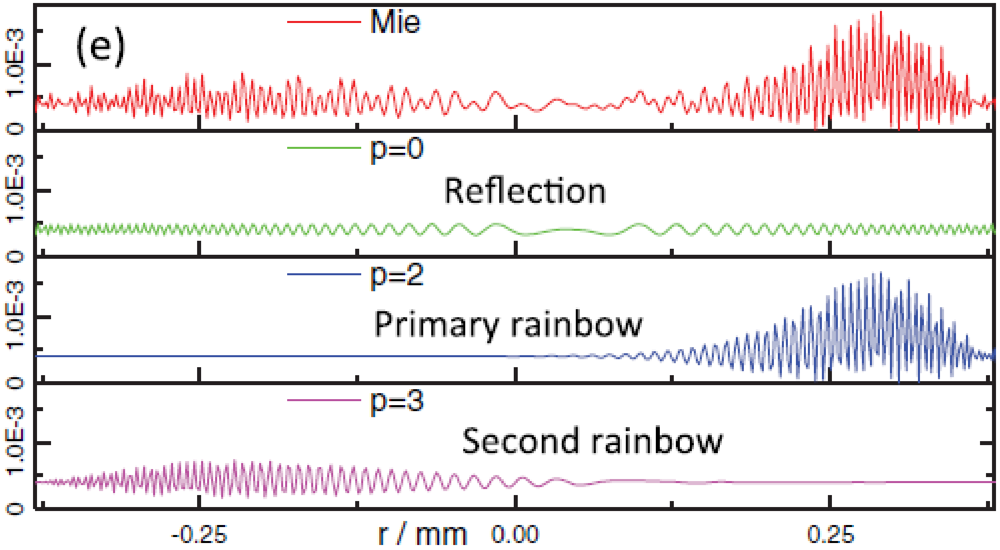
Mie scattering: $D_{\text{particle}} >> \lambda$

Rayleigh scattering: $D_{\text{particle}} \leq \lambda$

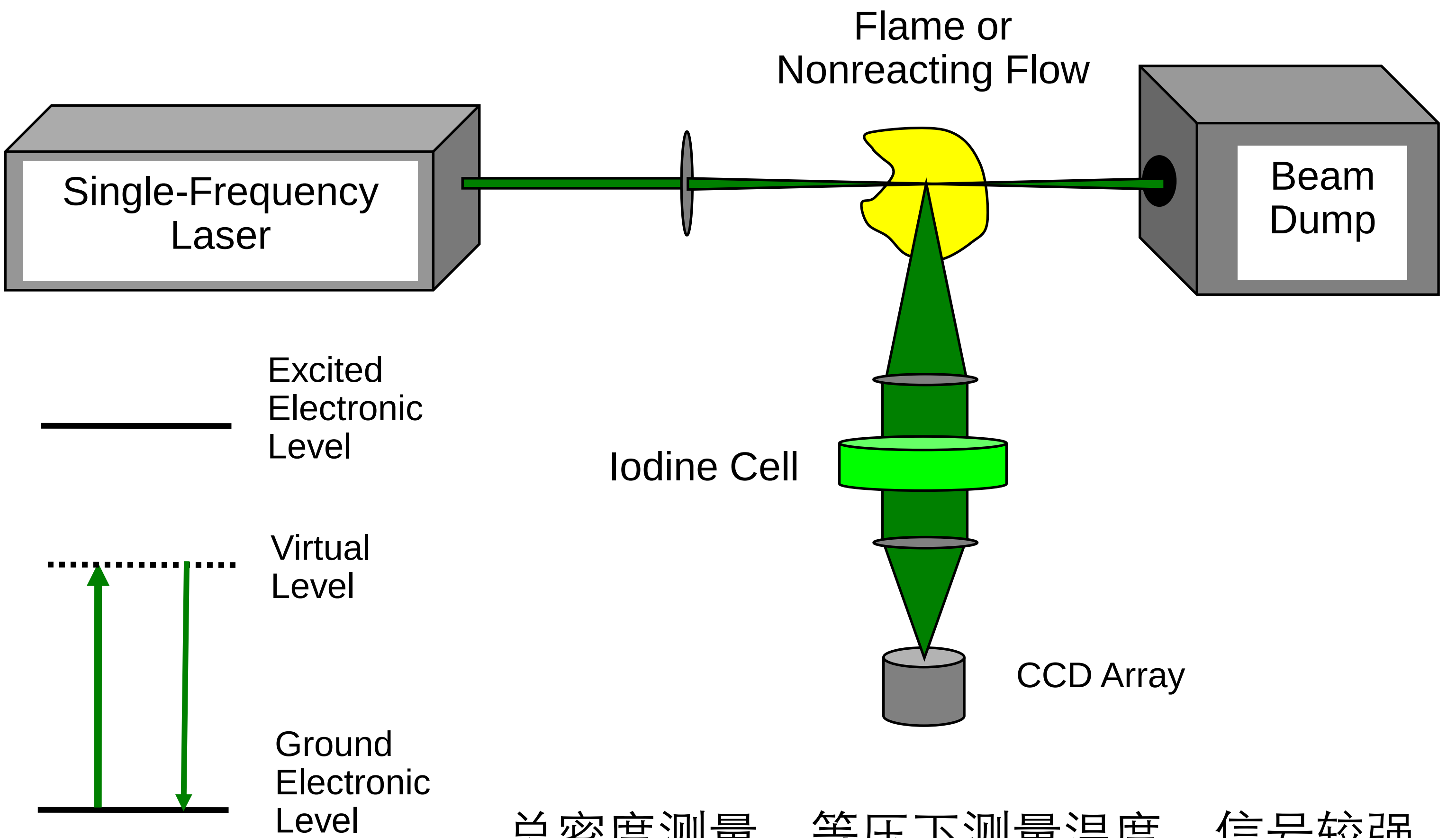
彩虹技术


p=0
reflection
p=1
particle
transmission
x,p
n=m₁/m₂
(m₁)
m₂
refraction
(primary rainbow)
p=2



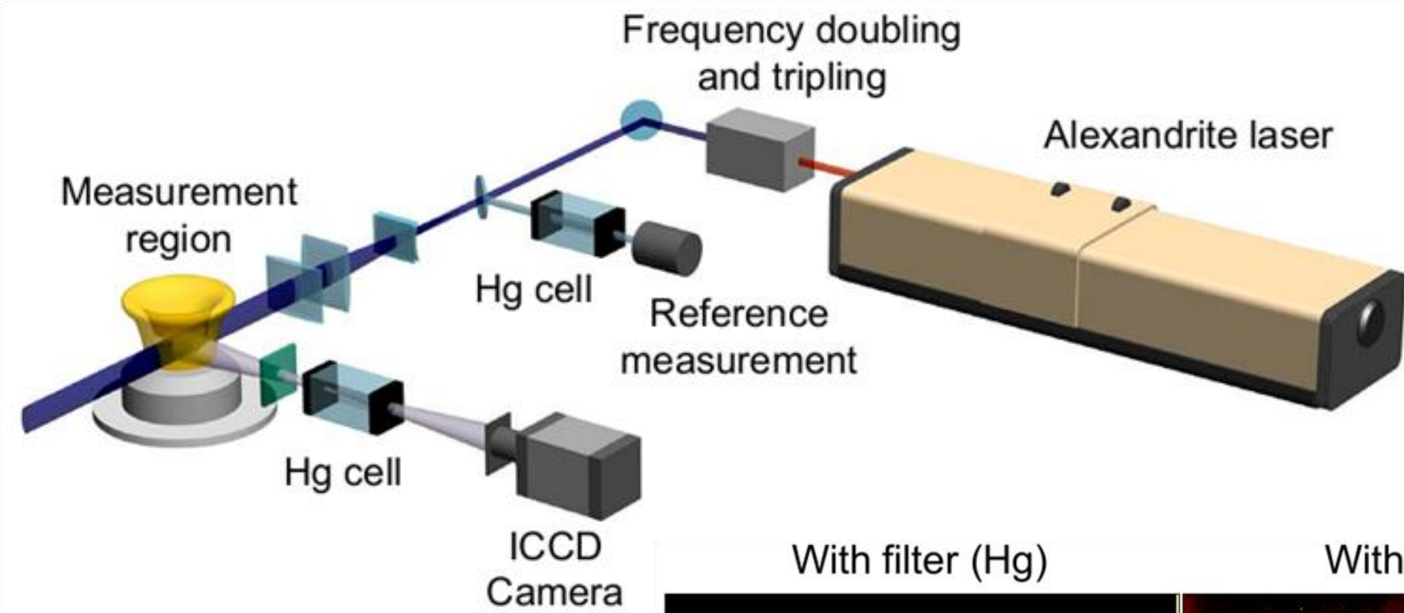

(e)
Mie
p=0
Reflection
p=2
Primary rainbow
p=3
Second rainbow
0
1.0E-3
-0.25
r / mm
0.00
0.25

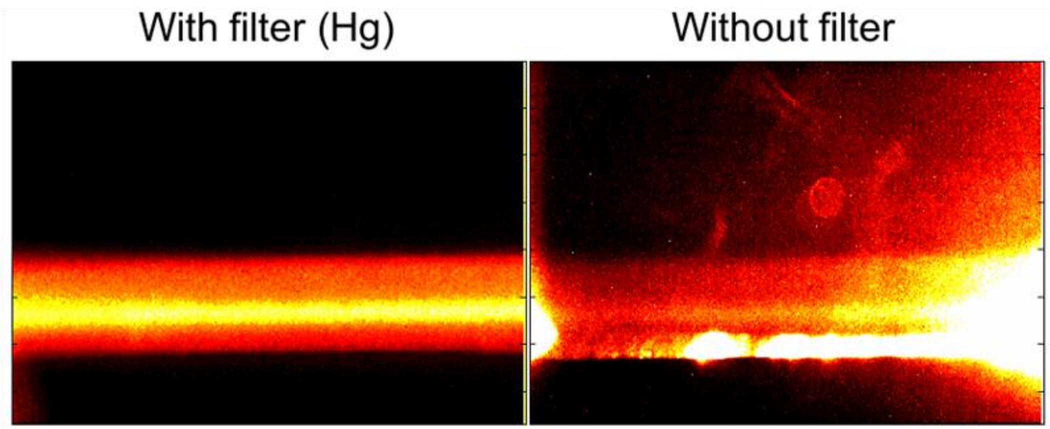
瑞利散射Rayleigh Scattering
– Filtered Rayleigh Scattering

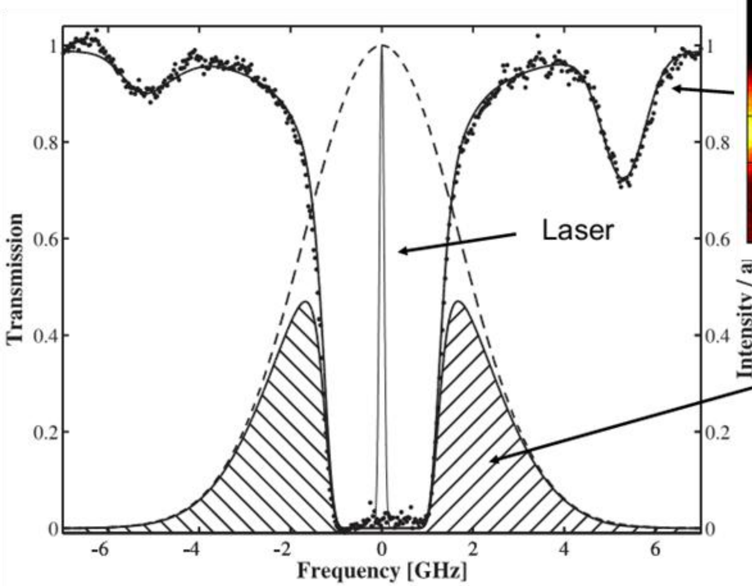


总密度测量，等压下测量温度，信号较强。

Strong signal, spatially resolved, not species-specific



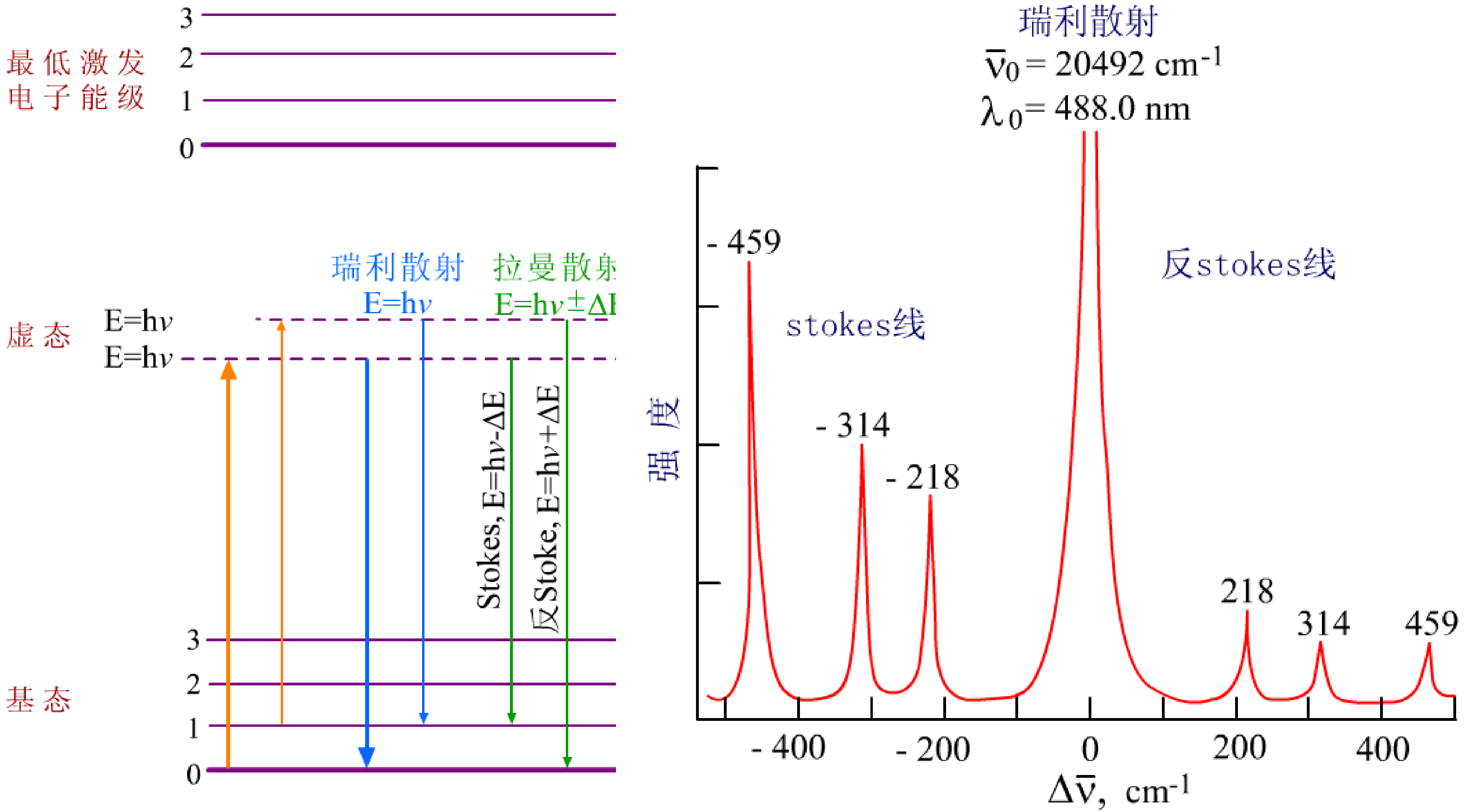


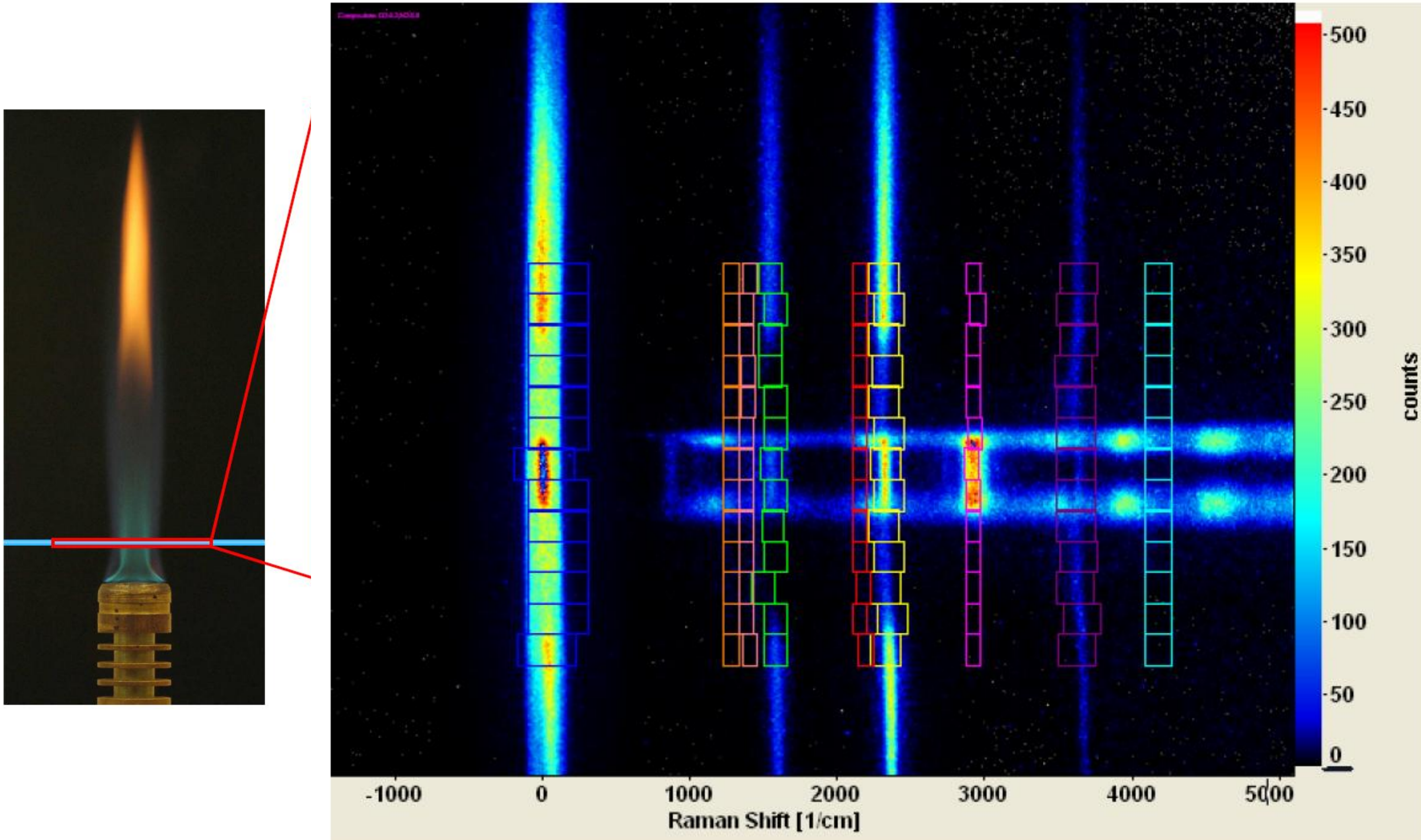


Dashed area is Rayleigh scattering from gas molecules in the flame (much broader than the laser)

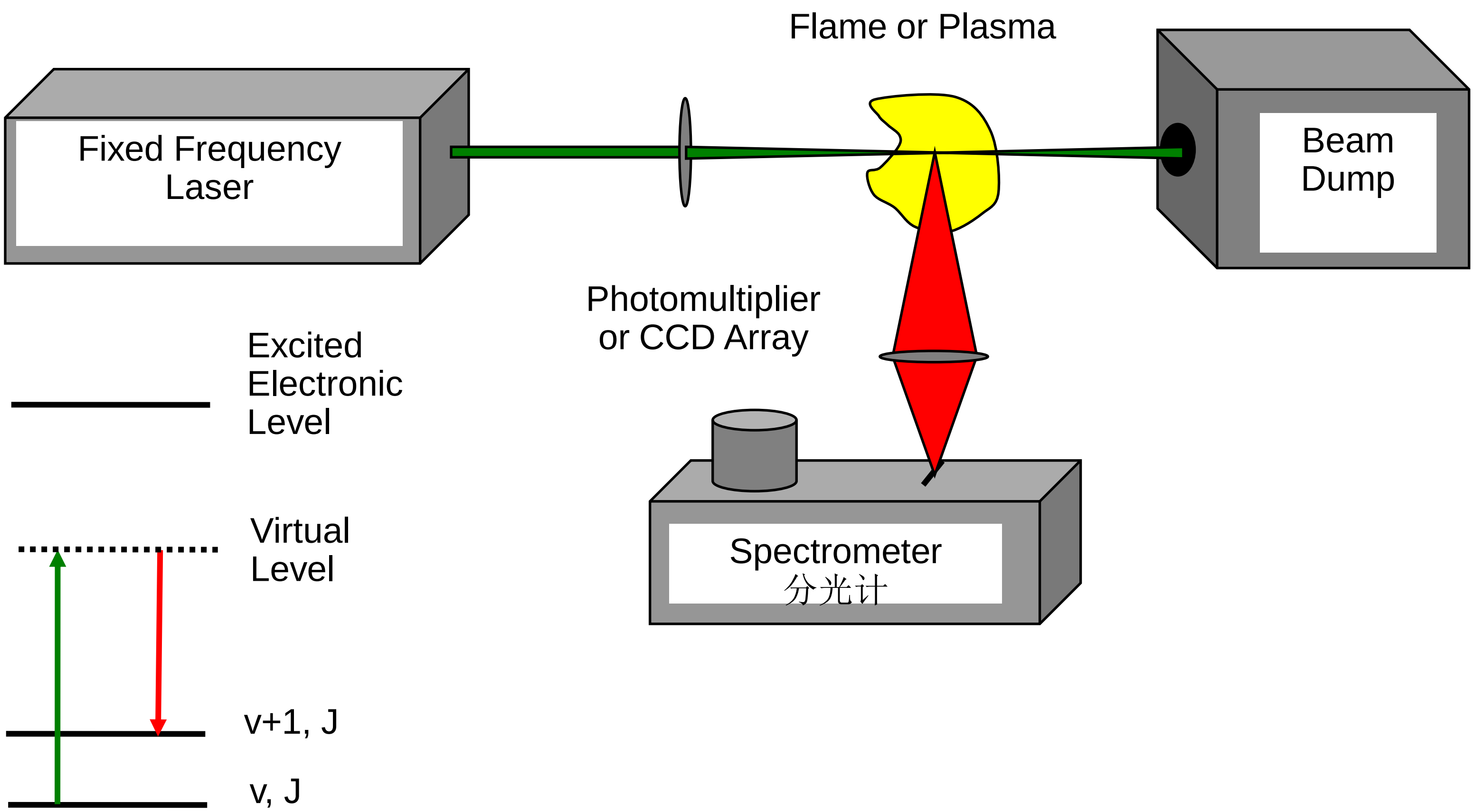
(Figure from J. Zetterberg)

自发拉曼散射
Spontaneous Raman Scattering

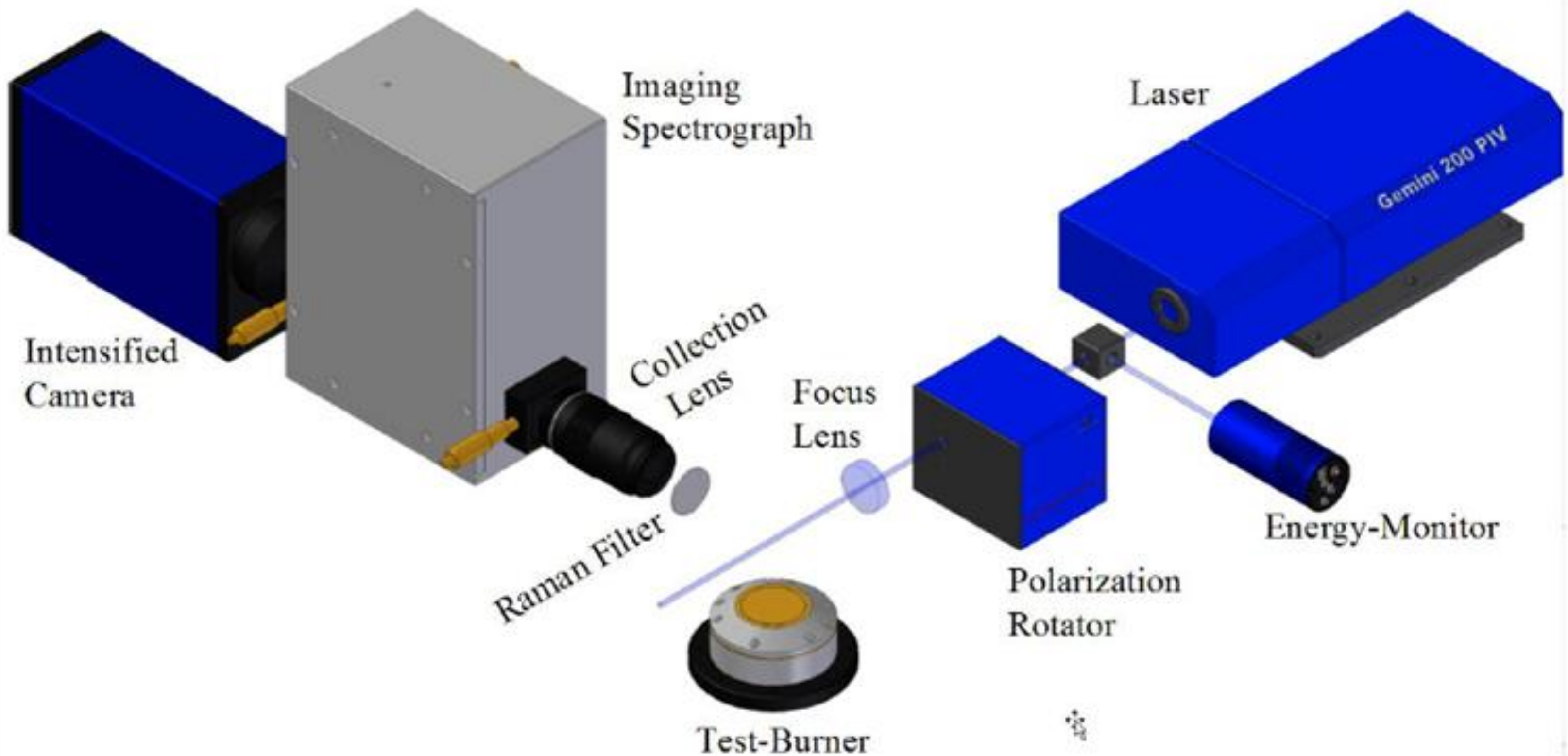




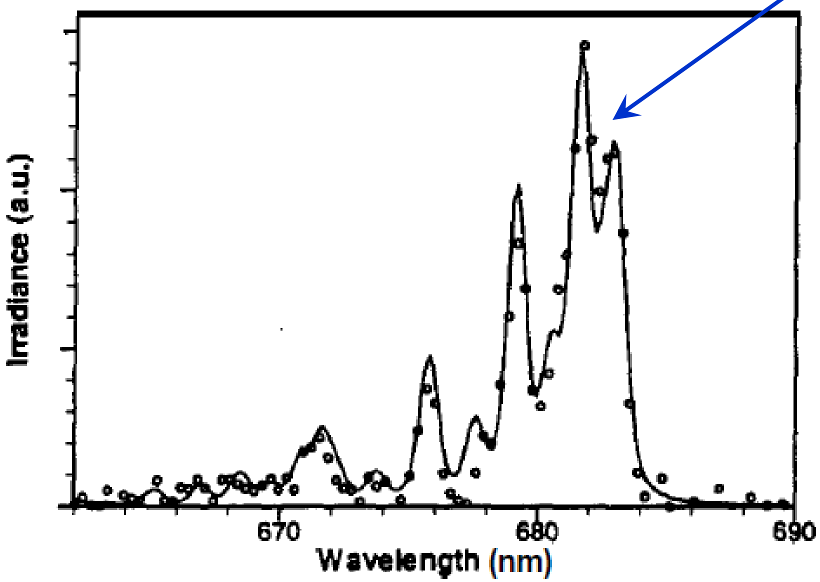
(a) Testing source image



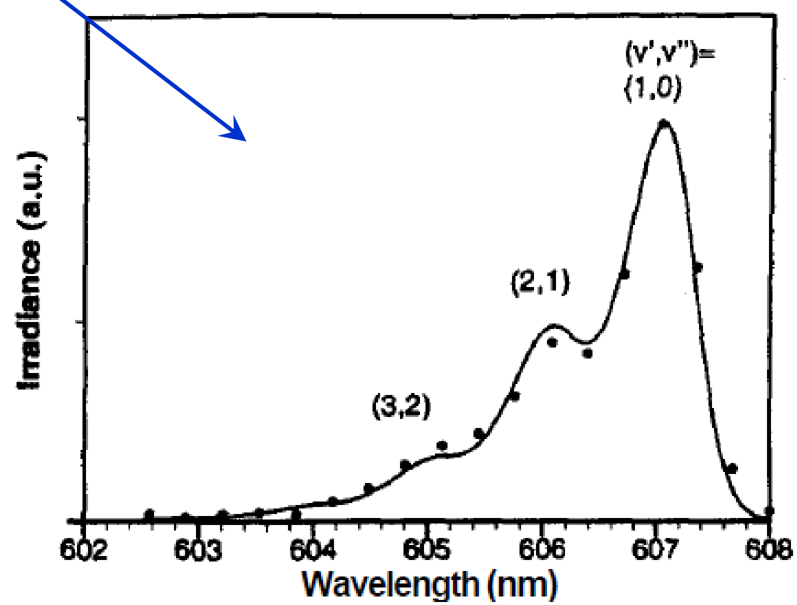
Species-specific, spatially resolved, quantitative, weak signal


Imaging
Spectrograph
Laser
Gemini 200 PIV
Intensified
Camera
Collection
Lens
Focus
Lens
Raman Filter
Energy-Monitor
Polarization
Rotator
Test-Burner

1889K



Ro-vibrational H_2 Raman spectra at 20 atm.



Vibrational N_2 Raman spectra at 20 atm

（1）谱带面积方法，已经在N2、H2O、CO2 组分上验证过，由激发态和基态的相对积分强度导出温度值；（2）谱带峰值强度方法，已经在N2和O2上验证过，通过转动激发态与基态的峰值强度之比来获取温度；（3）斯托克斯/反斯托克斯强度方法，特别是针对N2，通过斯托克斯Q分支与反斯托克斯Q分支积分的相对强度比率来确定温度；（4）谱线拟合方法，已用于N2、O2、CO2、H2O和H2的温度测量，通过最小二乘法拟合实验光谱和特定温度下的理论光谱。

Laser-Induced Fluorescence (LIF，激光诱导荧光)

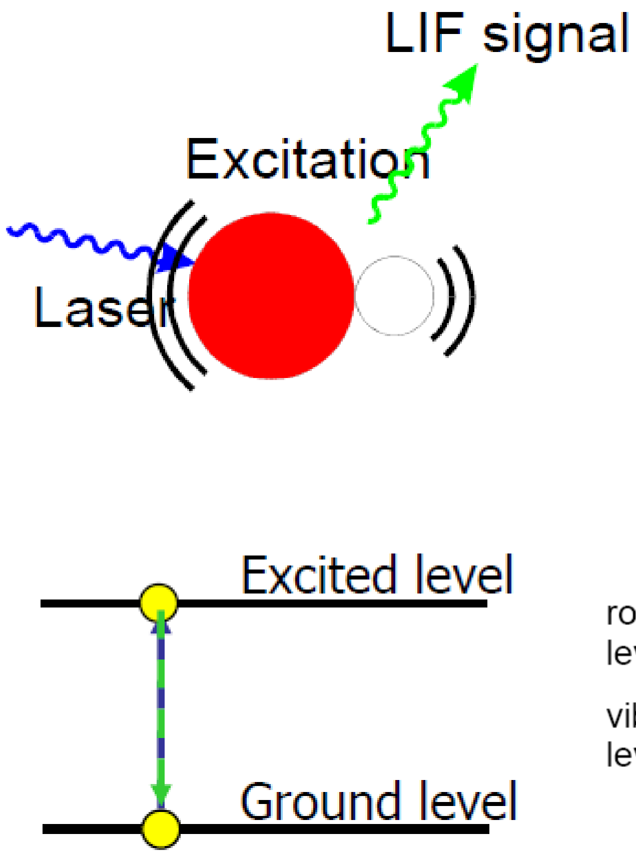
对被测对象所发出的由光源所激发（诱导）的荧光信号进行探测的实验技术都可以称作LIF。如果采用片状光源，则成为PLIF 。

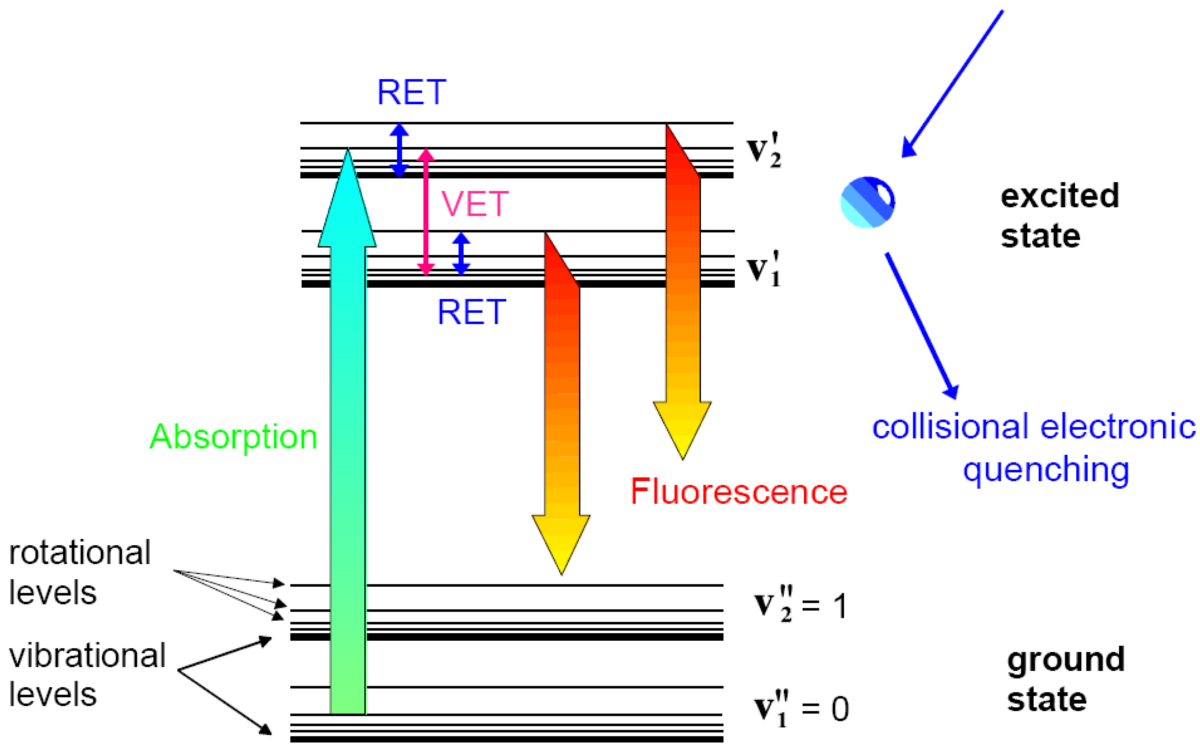
PLIF的分类

（1）示踪平面激光诱导荧光技术：在被测对象中人为地加入荧光染料的PLIF技术（Tracer PLIF）。测量总密度。最容易实现，设备造价最低。

（2）不依赖于外界加入的示踪物质，而是测量分析用激光激发流场物质本身的荧光。由于不同物质组分具有不同的激发波长，不同的荧光发射波长，所以这种技术可以分析物质的组分。例如可以分析燃烧过程中的OH, CO, NO, CH 等原子基团的密度分布。 设备造价昂贵，调试复杂。

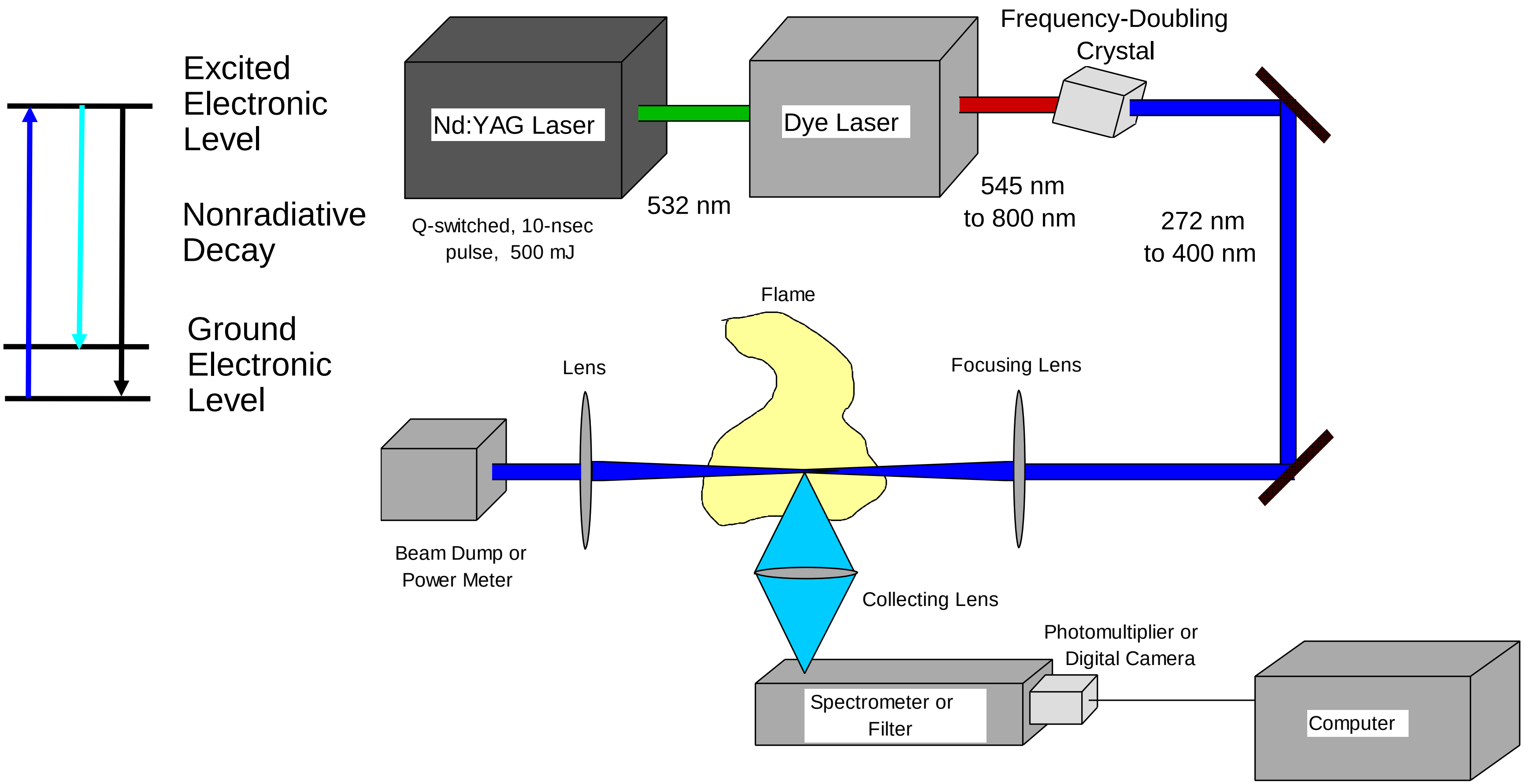
Laser-Induced Fluorescence (LIF)





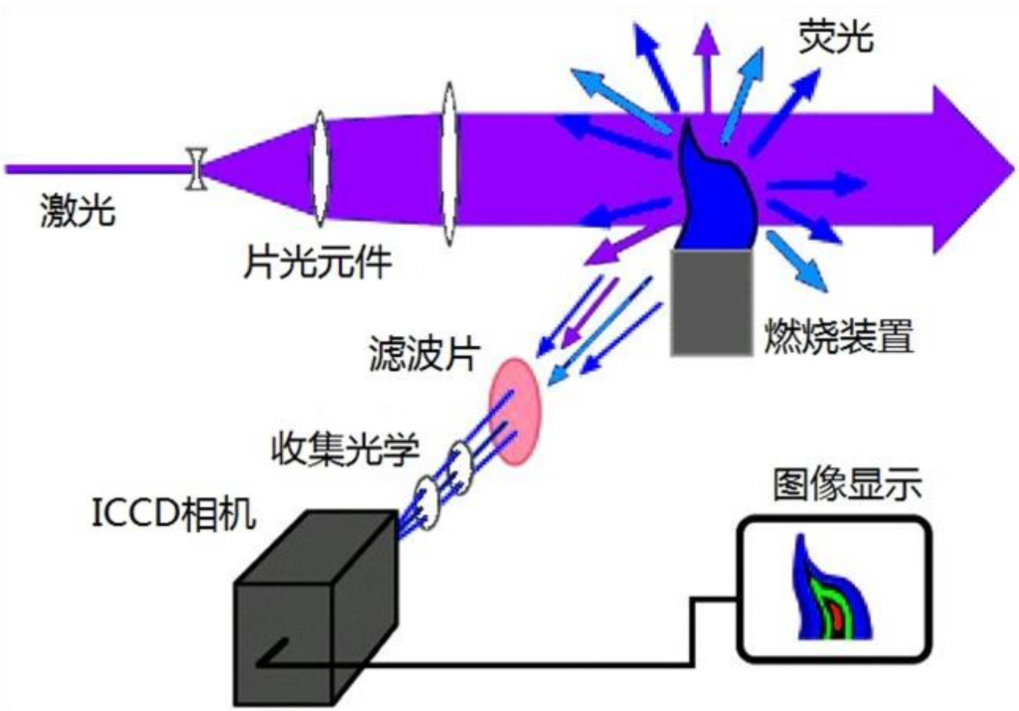
RET: rotational energy transfer

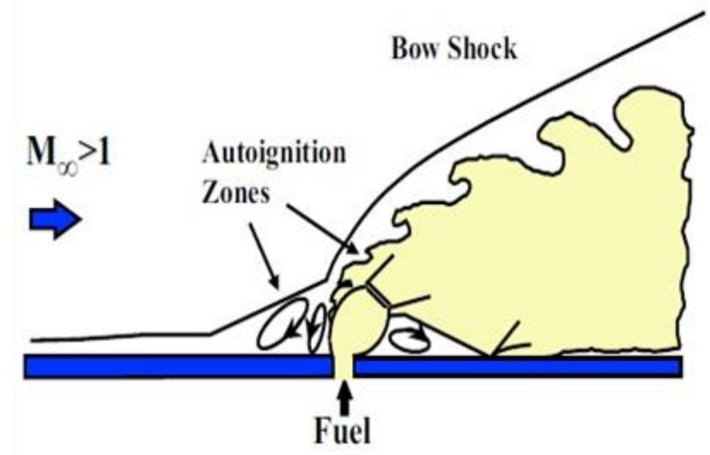
VET: vibrational energy transfer

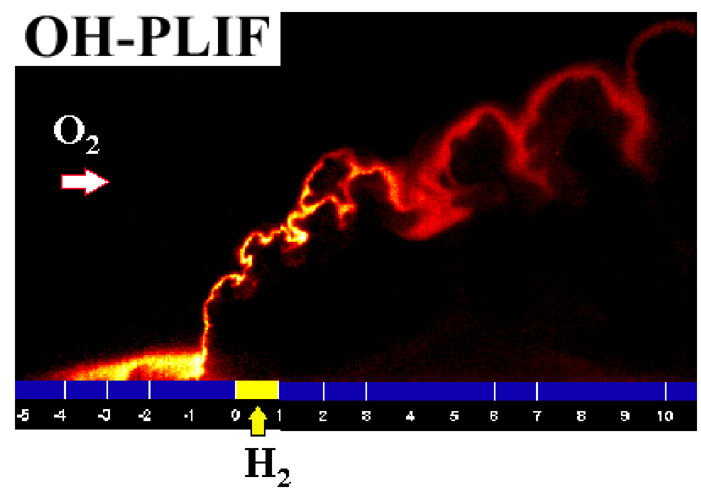


Species-selective, spatially resolved, strong signals, complicated by nonradiative decay, not all species fluoresce

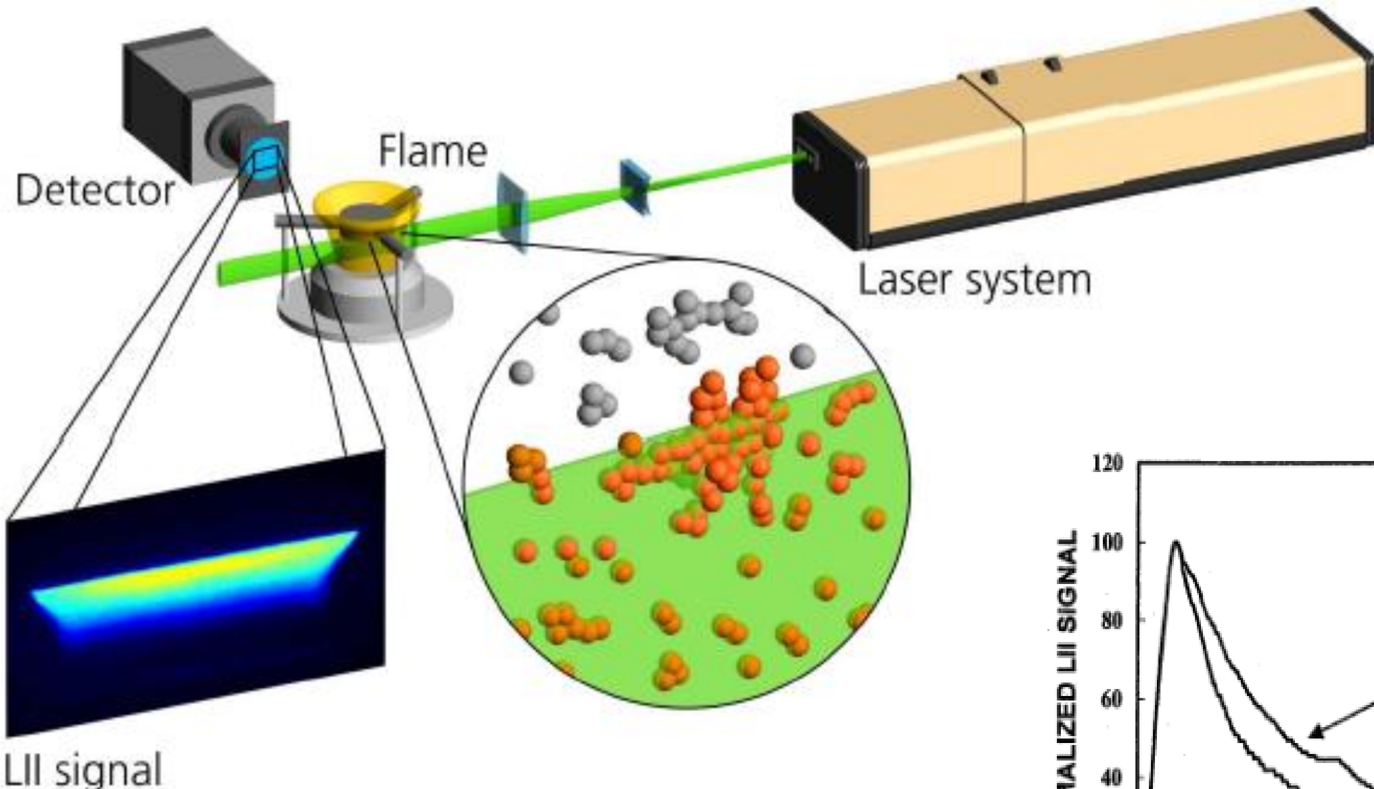
Planar Laser-Induced Fluorescence (PLIF)

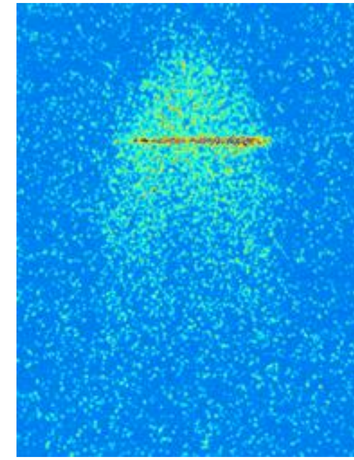


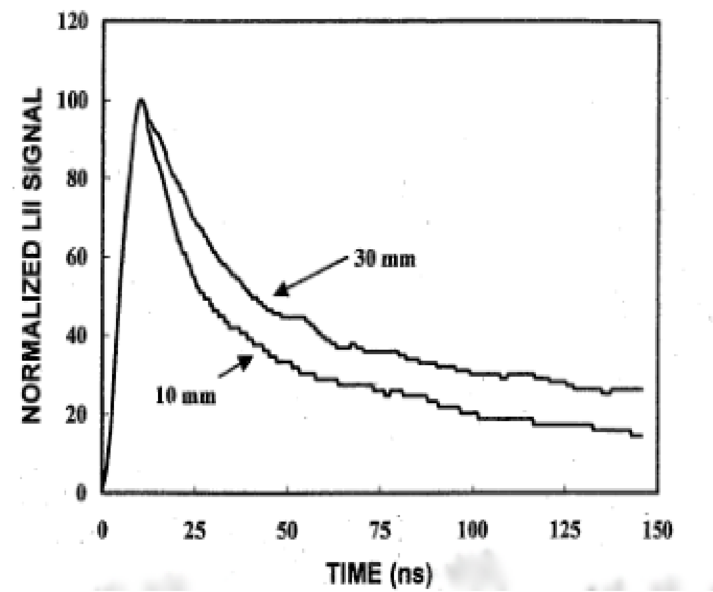




Laser-induced incandescence (LII)



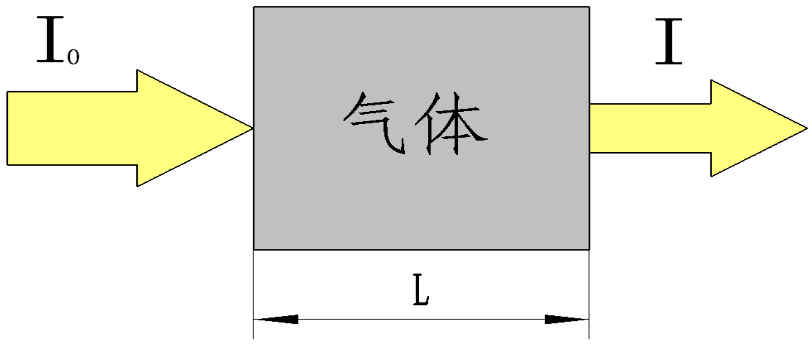




Laser Absorption（吸收光谱方法）

理论基础：Beer-Lambert定律

该定律描述了一束激光穿过气体介质入射光强与透射光强之间的关系

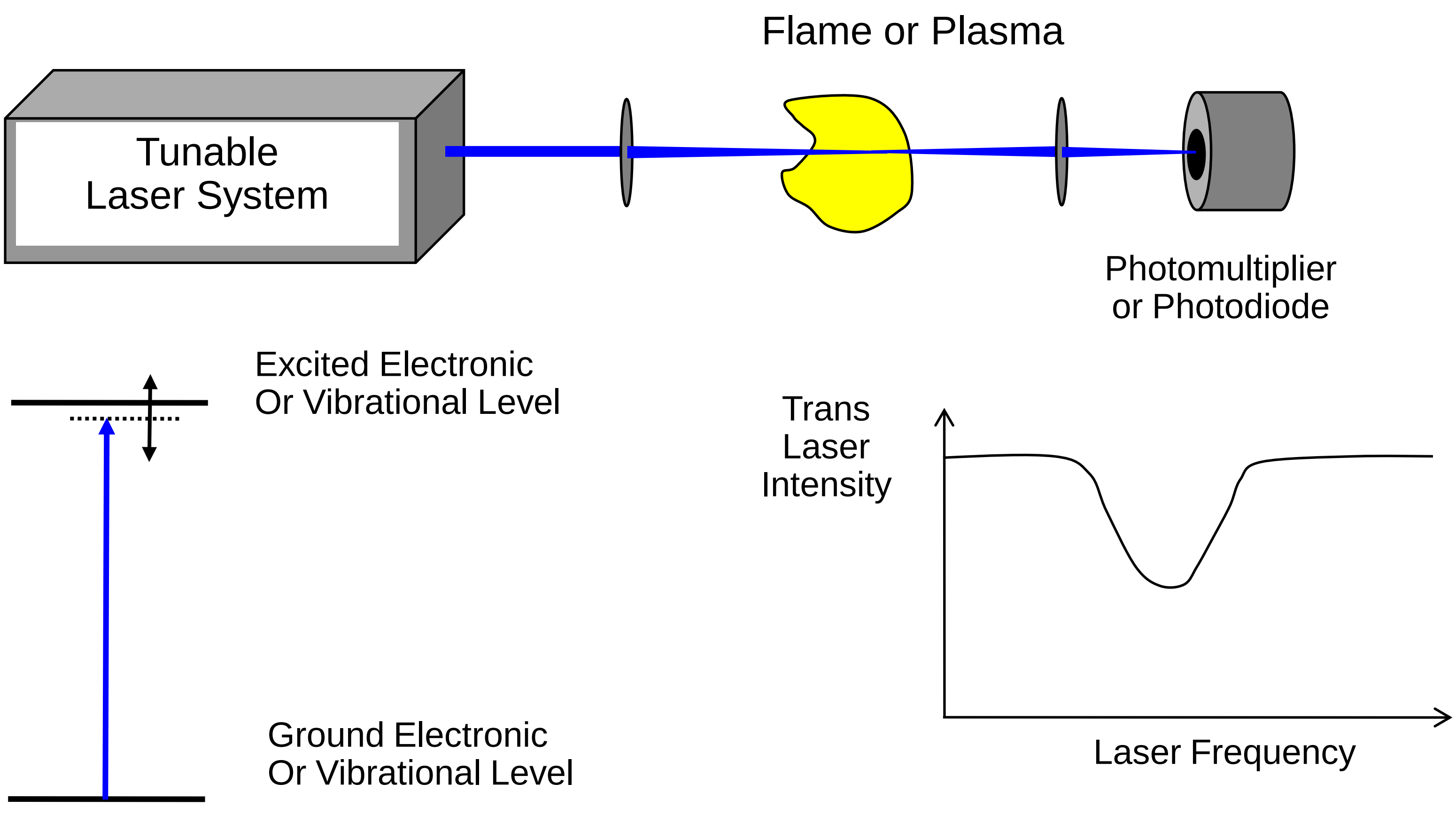


$$T_\nu = \left(\frac{I}{I_0}\right)_\nu = \exp\left(-k_\nu \cdot L\right)$$

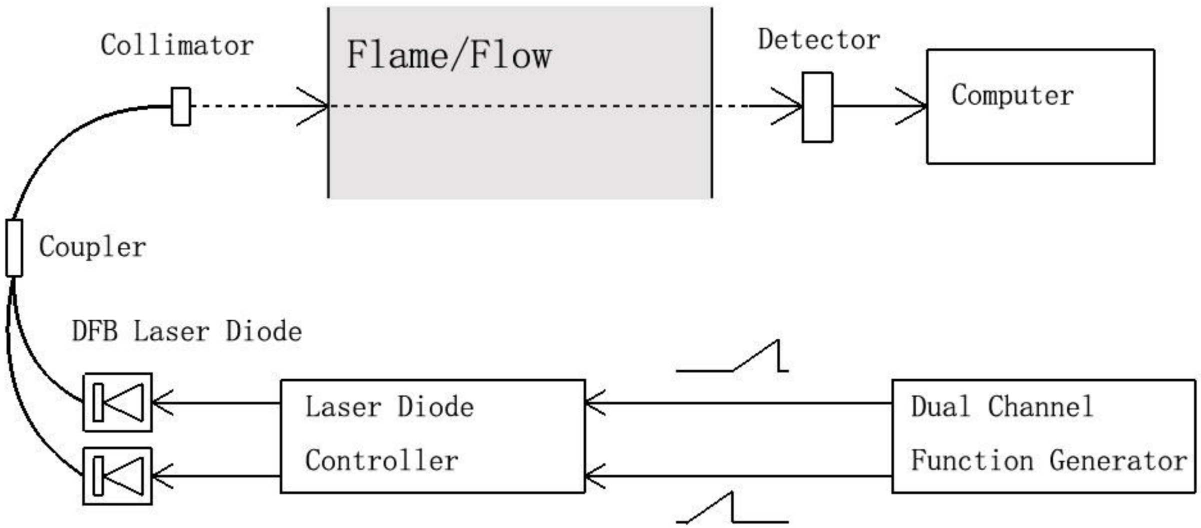
$$k_\nu = P\sum_{j=1}^{K} X_j \sum_{i=1}^{N_j} S_{i,j}(T)\phi_{i,j}\left(\nu - \nu_{0,i}\right)$$

可知，对特定组分，通过实验测量得到的吸收系数与压强、温度及组分浓度有关。

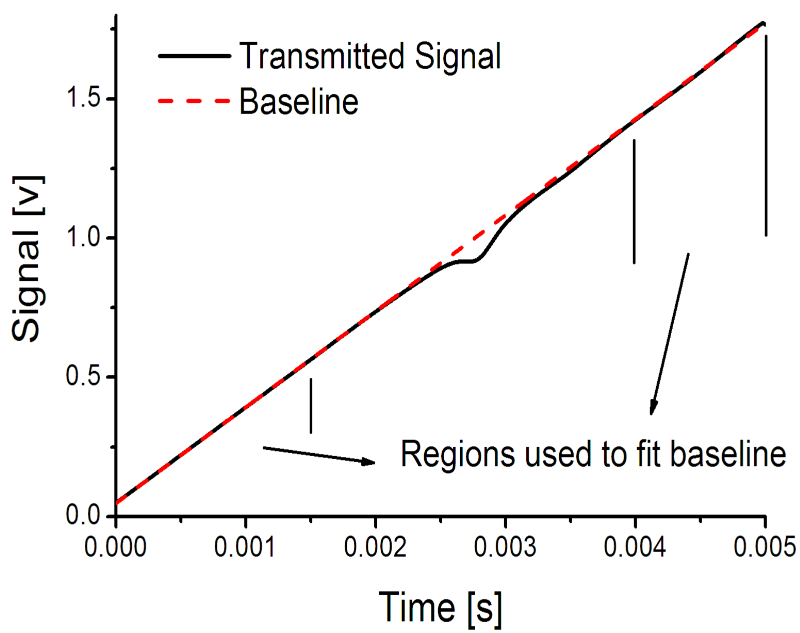
TDLAS（Tunable Diode Laser Absorption Spectroscopy）



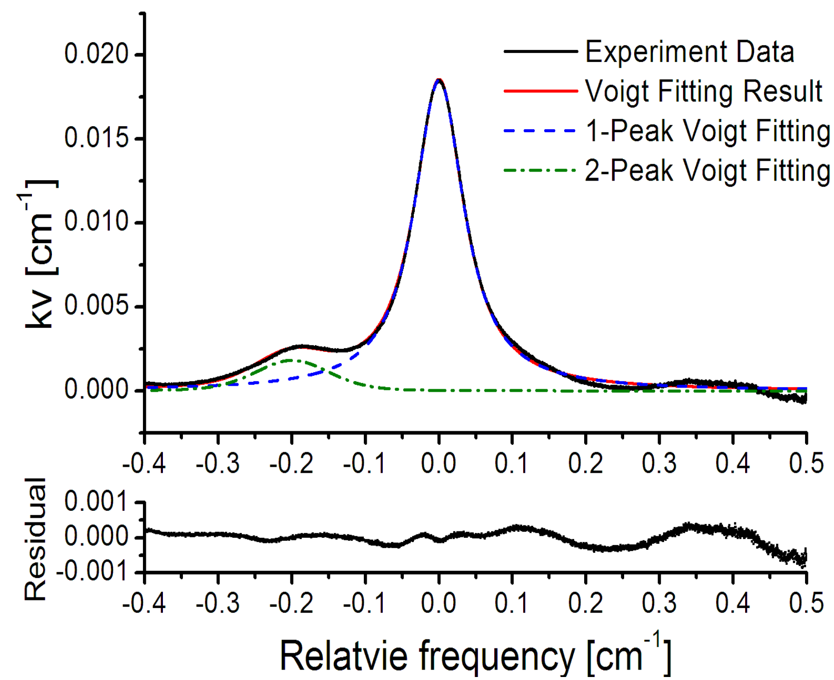
Species-specific, quantitative, path-averaged



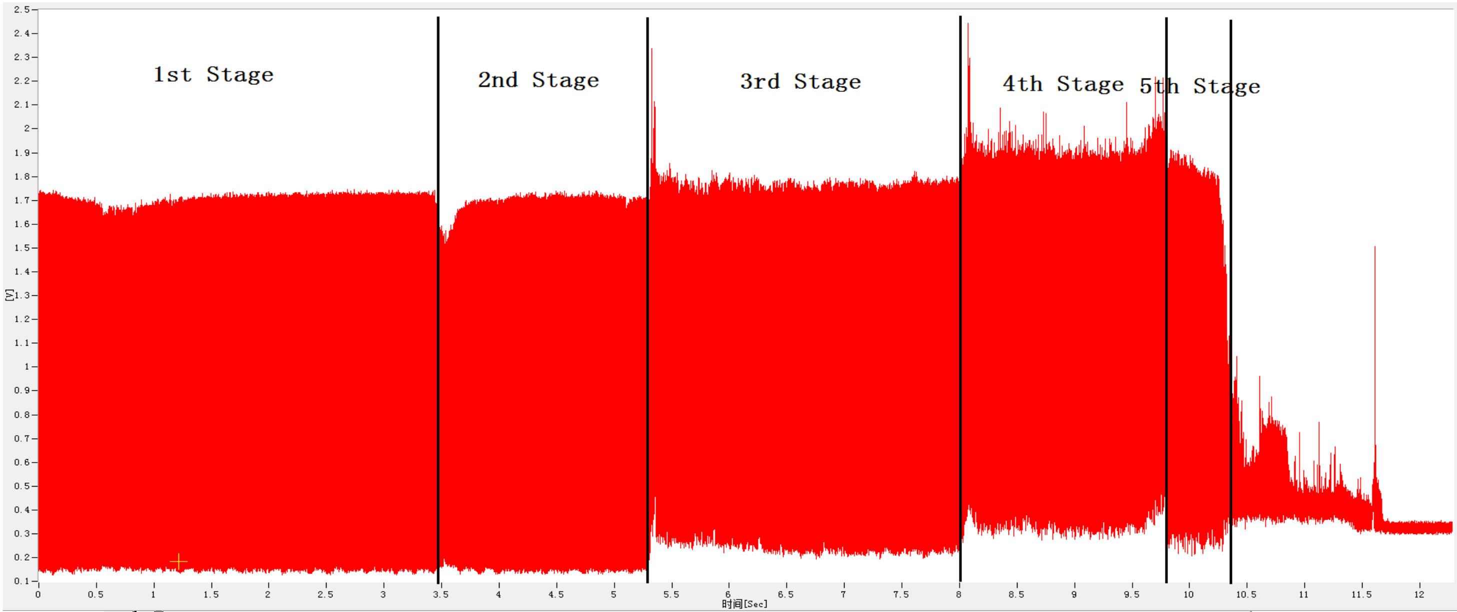
Collimator
Flame/Flow
Detector
Computer
Coupler
DFB Laser Diode
Laser Diode
Controller
Dual Channel
Function Generator

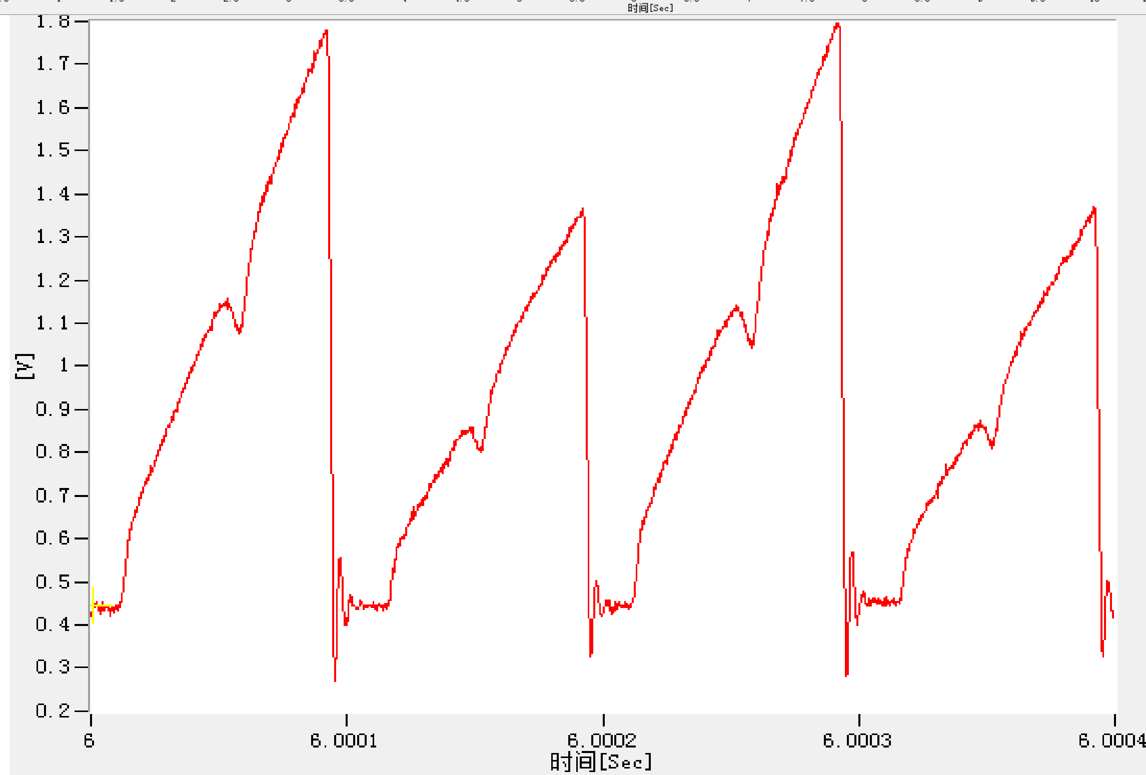


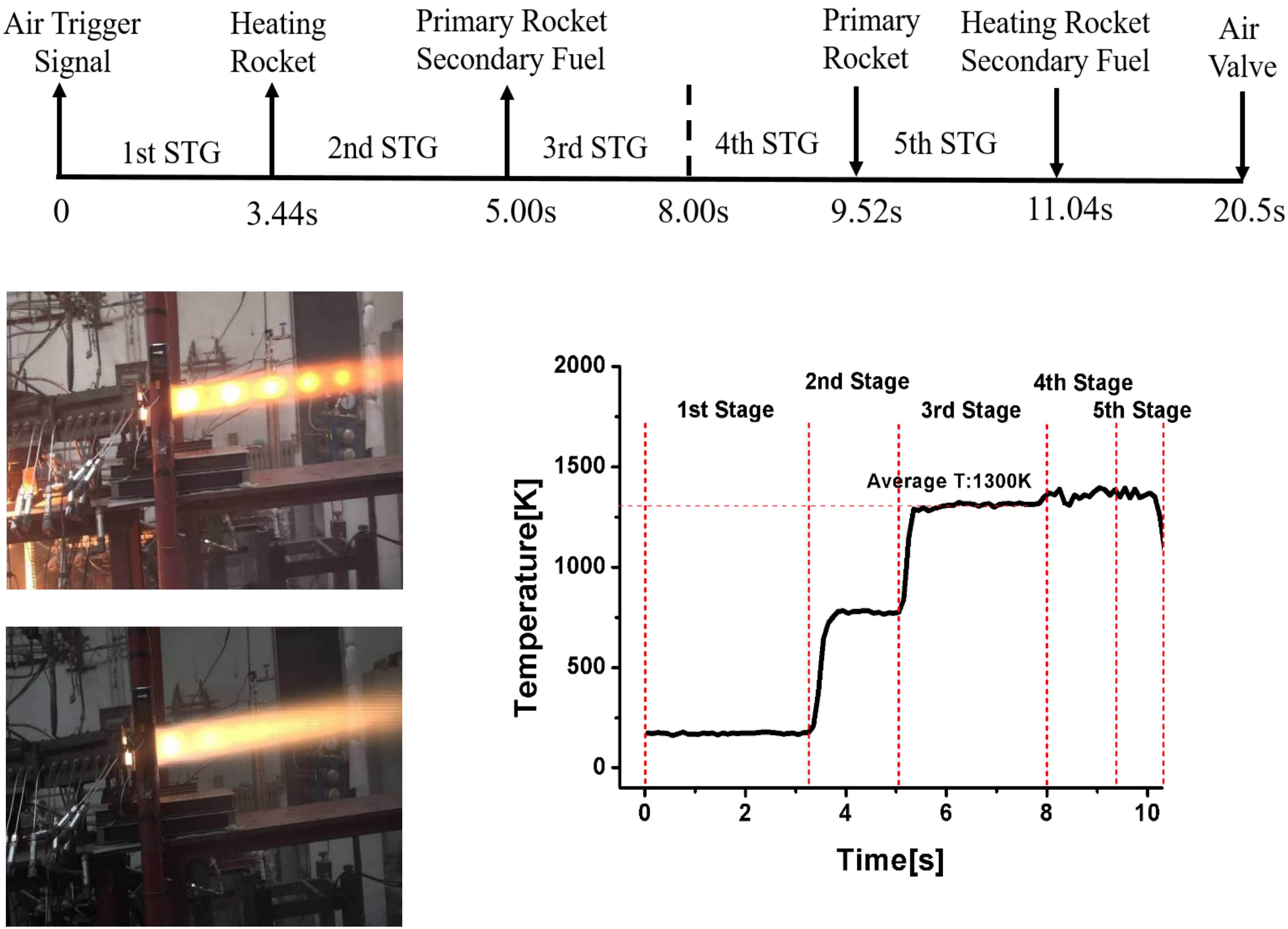
Transmitted Signal
Baseline
Regions used to fit baseline
Signal [v]
Time [s]
0.0
0.5
1.0
1.5
0.000
0.001
0.002
0.003
0.004
0.005



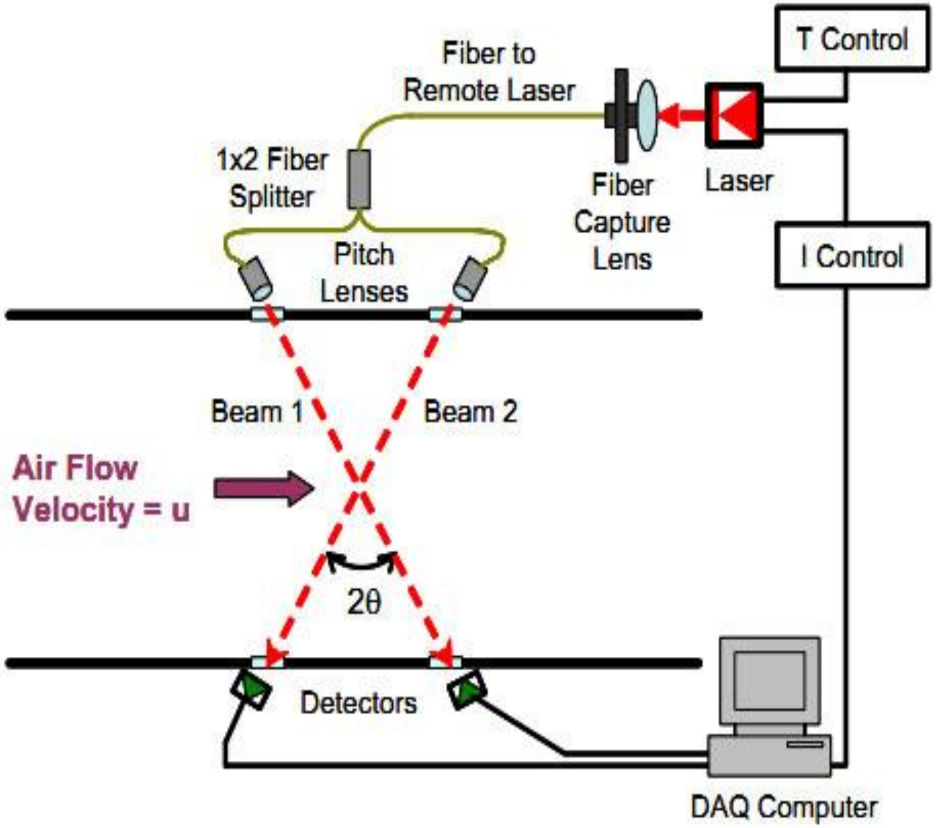
Experiment Data
Voigt Fitting Result
1-Peak Voigt Fitting
2-Peak Voigt Fitting
kv [cm^{-1}]
0.000
0.005
0.010
0.015
0.020
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
Residual
0.001
0.000
-0.001
Relatvie frequency [cm^{-1}]


1st Stage
2nd Stage
3rd Stage
4th Stage
5th Stage
[V]
时间[Sec]

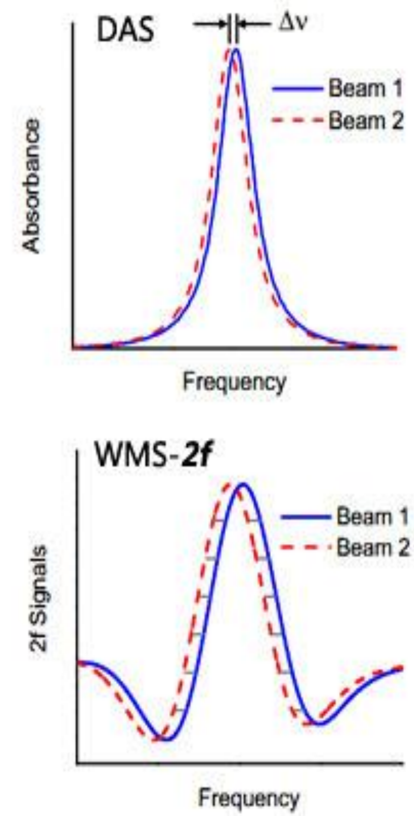

1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
[V]
6
6.0001
6.0002
6.0003
6.0004
时间[Sec]



Air Trigger Signal
Heating Rocket
Primary Rocket Secondary Fuel
Primary Rocket
Heating Rocket Secondary Fuel
Air Valve
1st STG
2nd STG
3rd STG
4th STG
5th STG
0
3.44s
5.00s
8.00s
9.52s
11.04s
20.5s
2000
1500
1000
500
0
Temperature[K]
1st Stage
2nd Stage
3rd Stage
4th Stage
5th Stage
Average T:1300K
0
2
4
6
8
10
Time[s]



(a) Schematic of velocity/mass flux sensor

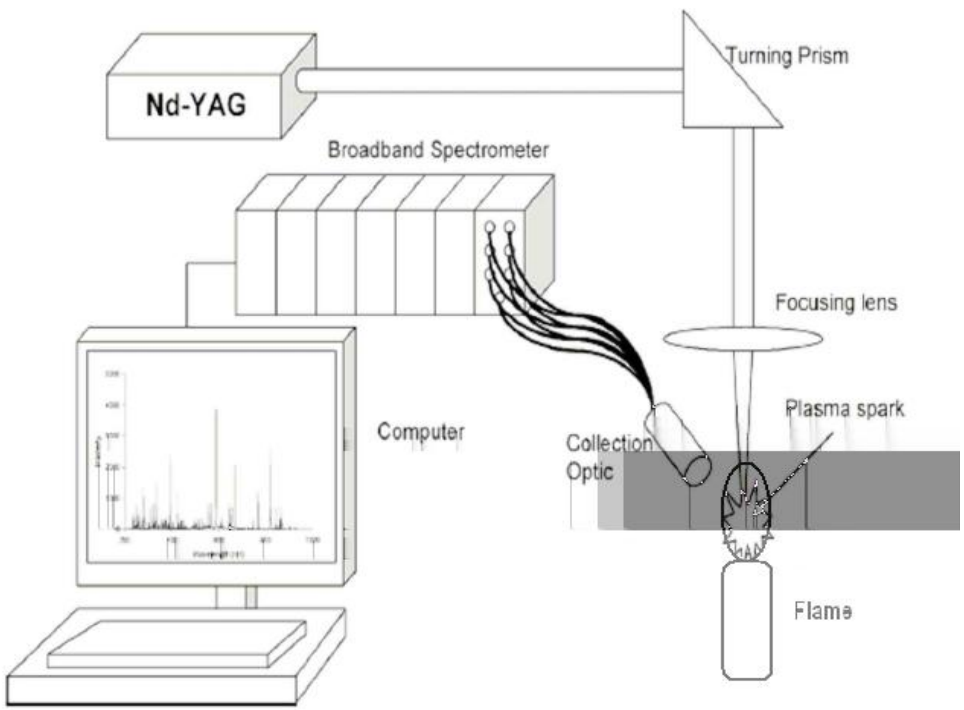


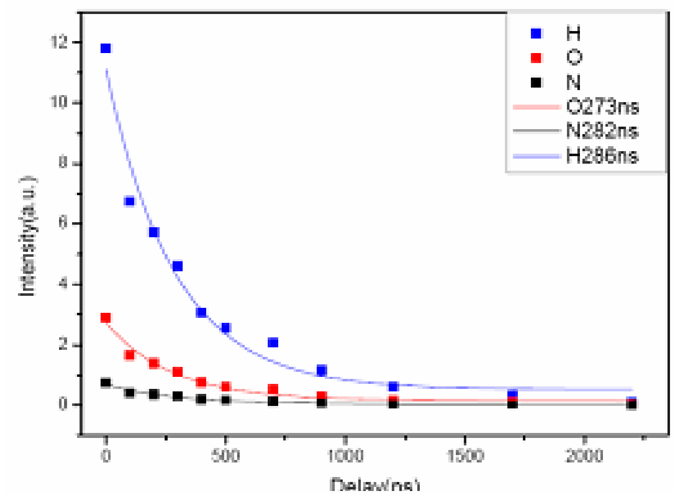
(b) Schematic of typical measurements

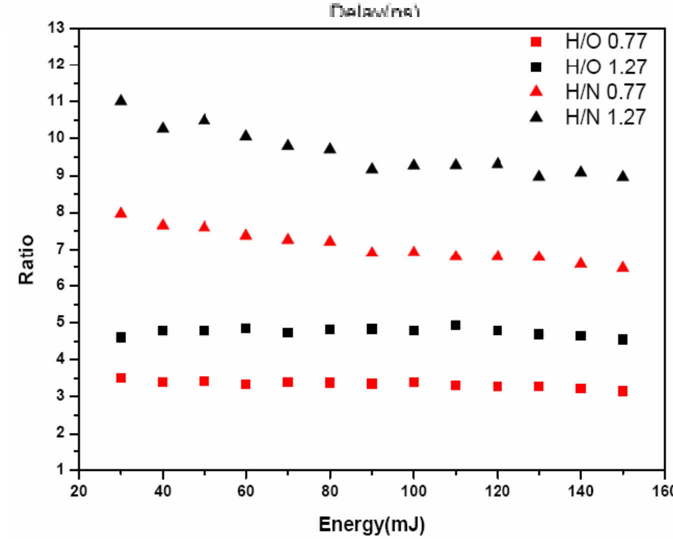
$$\Delta v = v_0 (2\sin\theta)\frac{u}{c}$$

激光诱导击穿光谱

Laser-induced Breakdown Spectroscopy (LIBS)



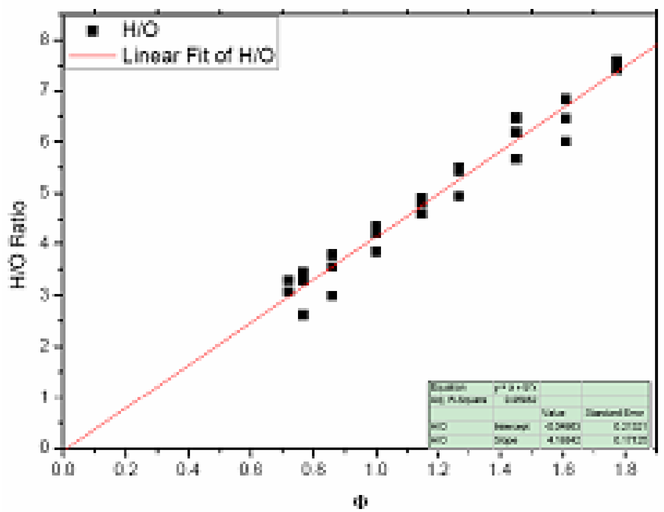


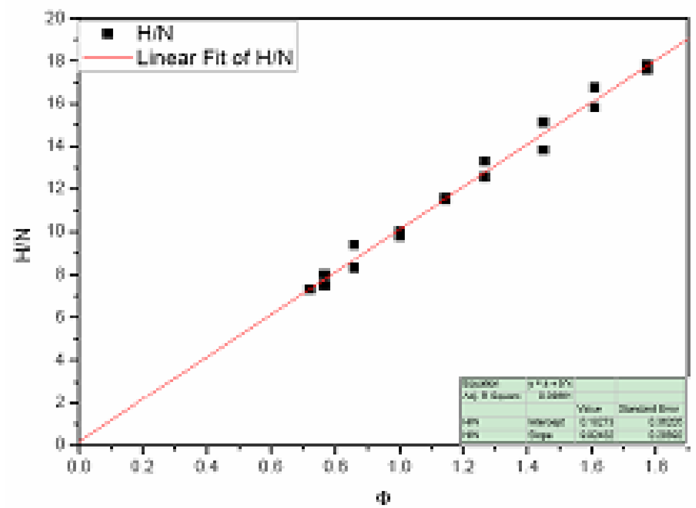


原子谱线衰减很快但相对强度比值稳定。

激光诱导击穿光谱

Laser-induced Breakdown Spectroscopy (LIBS)





原子相对强度比与火焰燃料当量比的对应关系

可用于吸气式发动机、液体火箭发动机局部混合比测量。

- 随着研究的深入，国家在发动机燃烧方面投入巨大，对先进燃烧诊断技术有很大的需求；
- 燃烧诊断技术学科交叉性强，很具有挑战性。

谢谢关注!

2017年5月