

第一届全国青年燃烧学术会议

激光光谱技术在燃烧中的应用

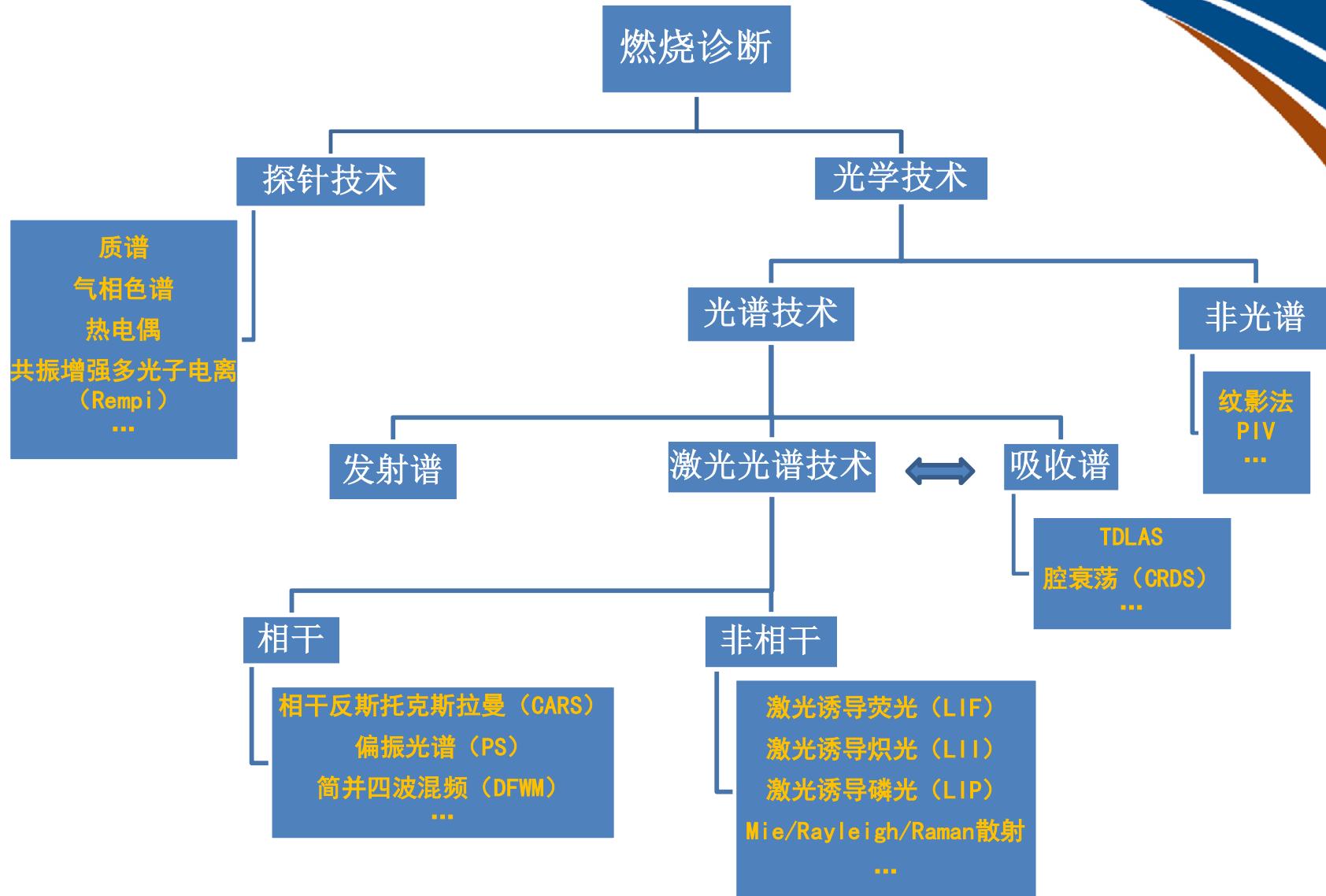
李博

boli@tju.edu.cn

2015-09-20 上海



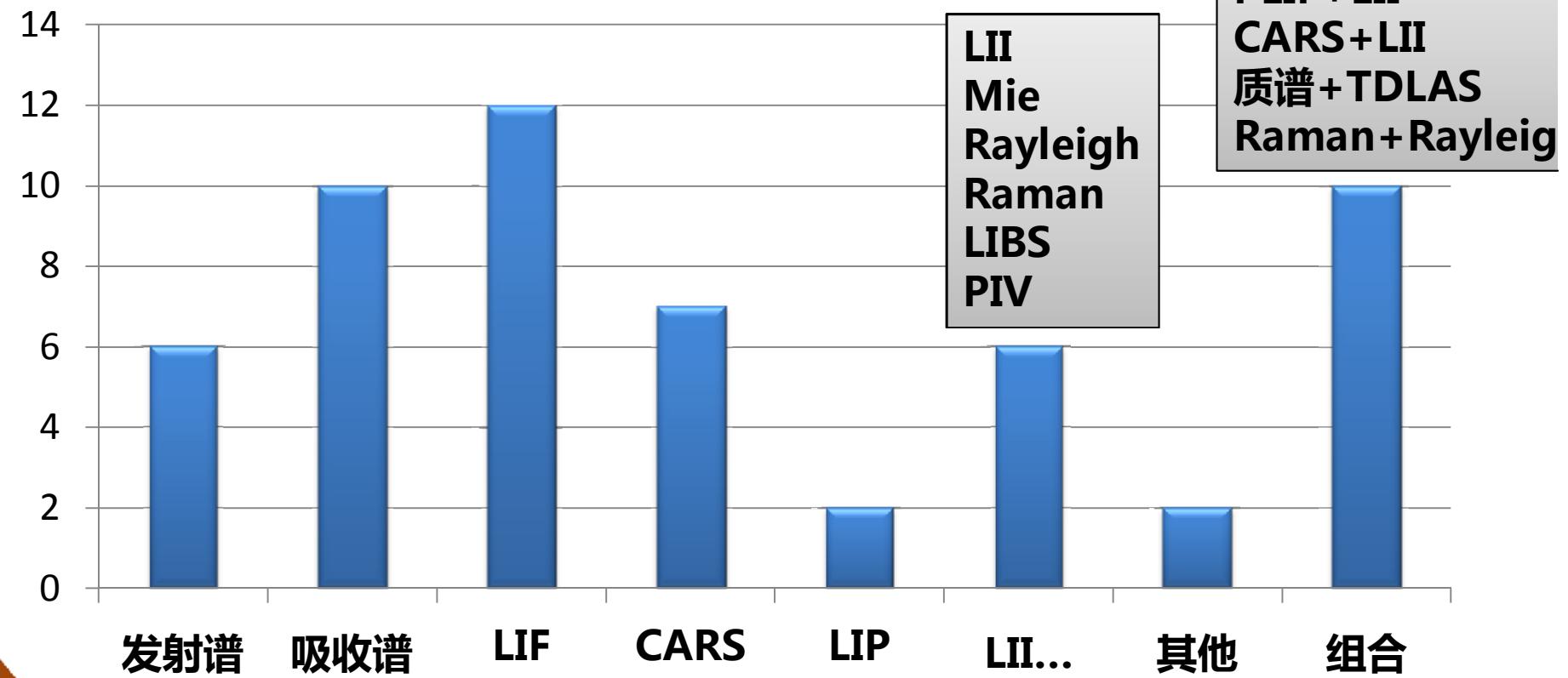
内燃机燃烧学国家重点实验室



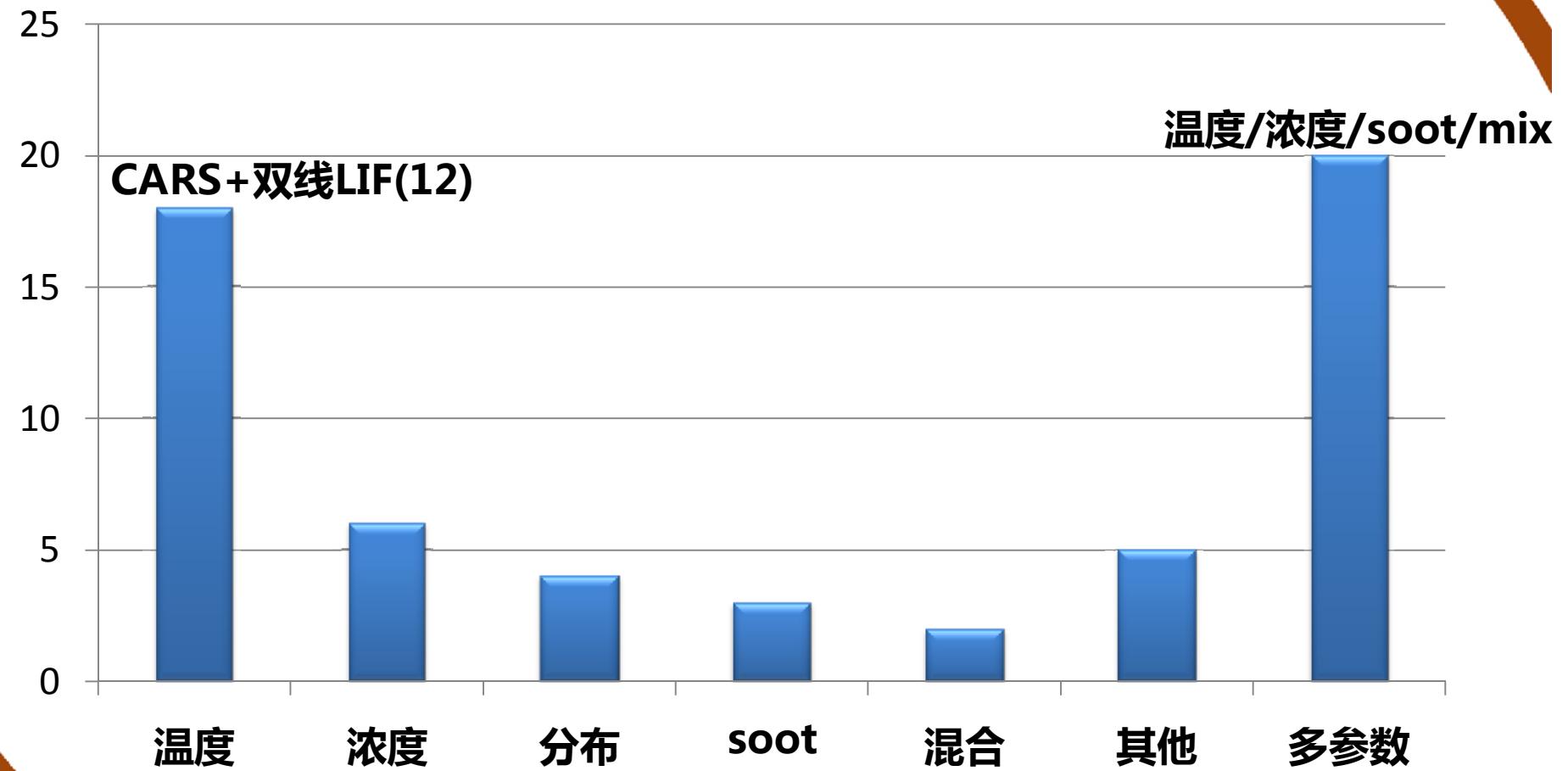
激光技术所能测量的物理量

实验技术	物理量	维度
PIV	• 速度场	2D, 3D
LIF	• 中间产物分布/浓度 (OH, CH ₂ O, NO, CH, tracer, PAH) • 温度	2D
Raman	• 主要中间产物浓度 • Mixture fraction • 温度	0D, 1D
CARS	• 测温	0D
LII	• 粒子 (soot) 特性 : 例如volume fraction, primary particle size	2D
TDLAS	• 中间产物浓度 • 温度	line-of-sight, 2D
LIBS	• 原子浓度	0D

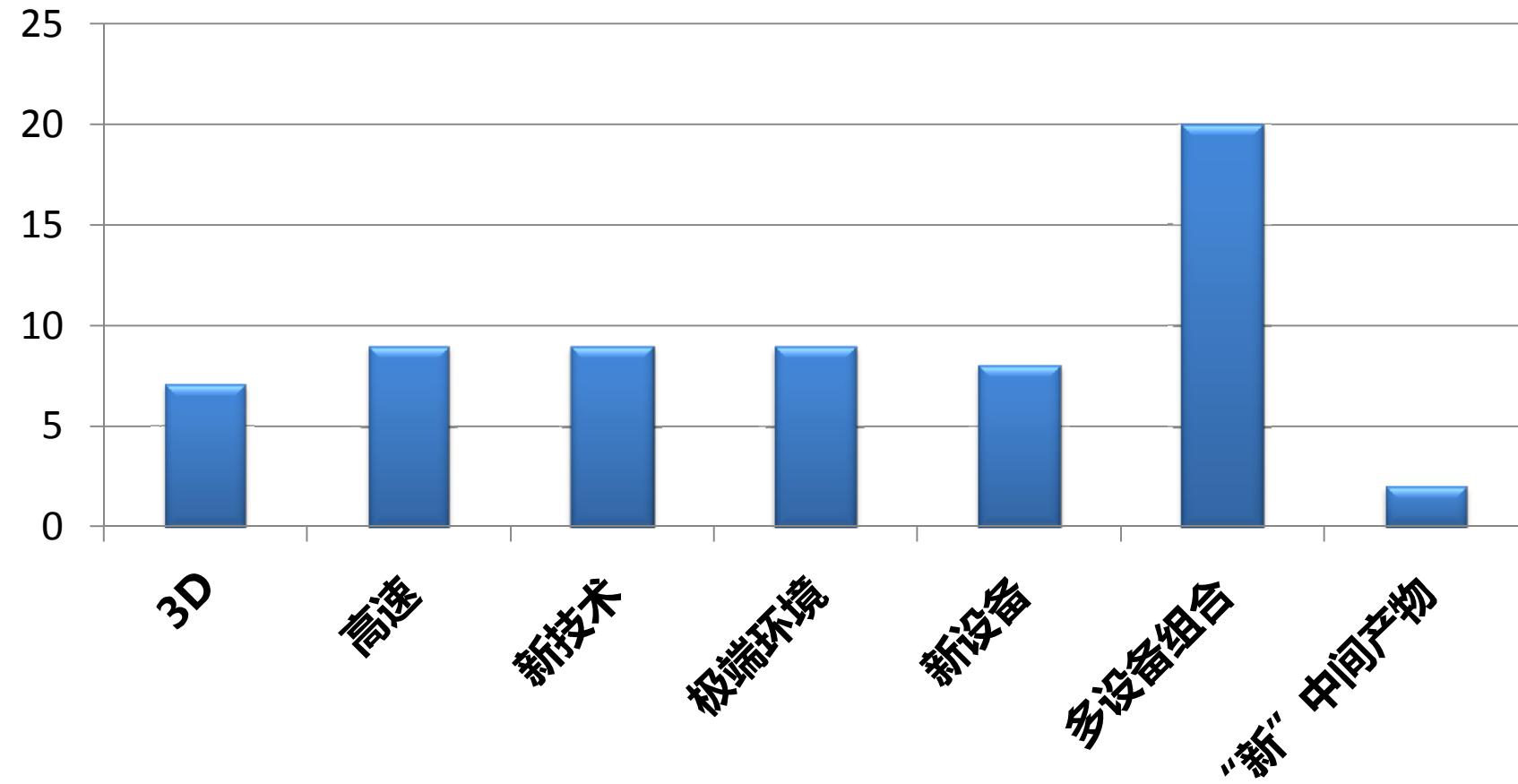
过去3届PCI燃烧诊断专题的一些统计数据：测试技术



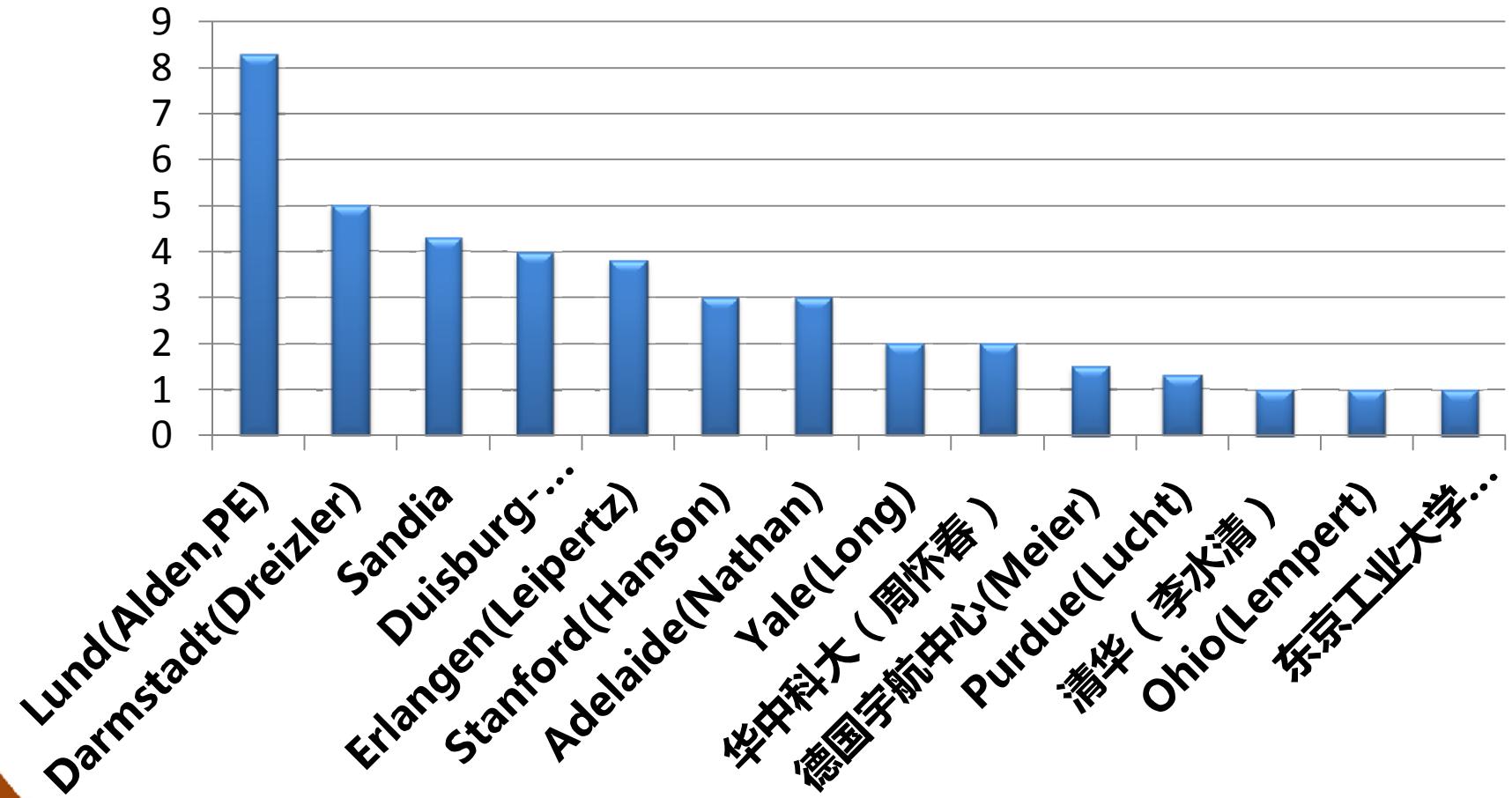
过去3届PCI燃烧诊断专题的一些统计数据：物理量



过去3届PCI燃烧诊断专题的一些统计数据：前沿问题



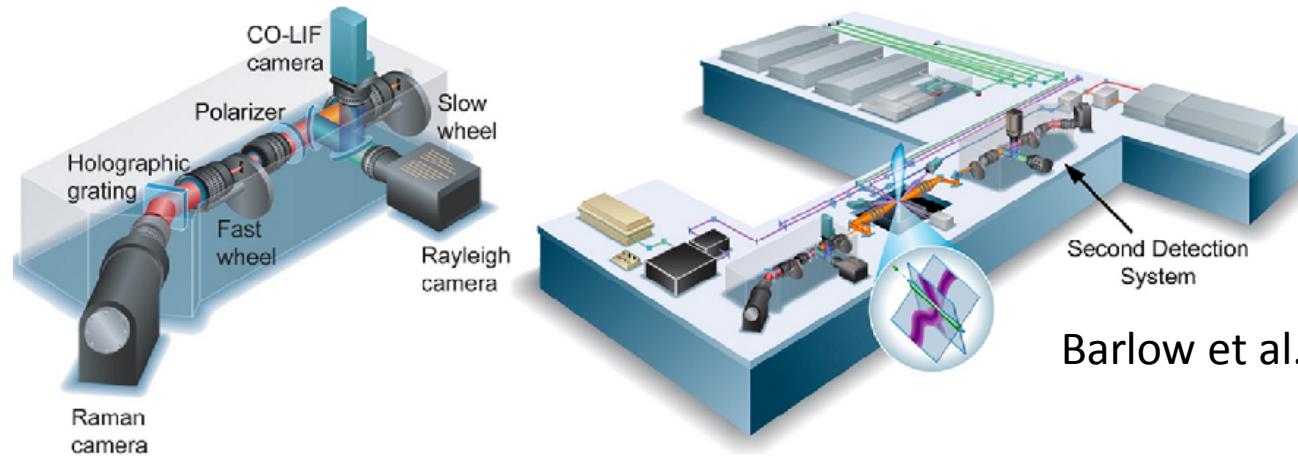
过去3届PCI燃烧诊断专题的一些统计数据：著名研究机构



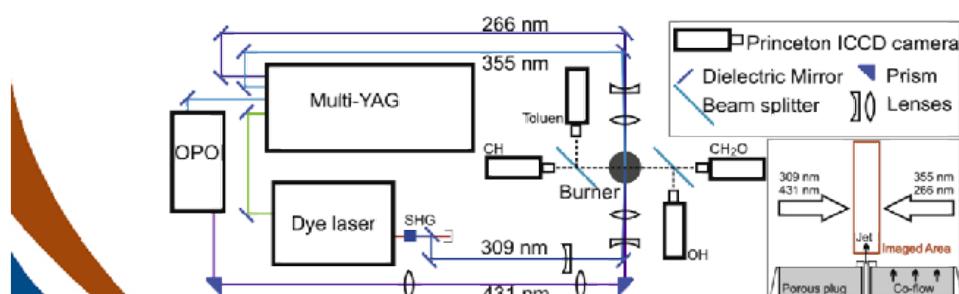
燃烧激光诊断技术面临的挑战（发展趋势）

- **多场多组分同时测量**
- **3D可视化(3D + t)**
- **高速测量**
- **精确2D测温**
- **恶劣环境测量（粒子/壁面杂散光、高压、有限/无光学窗口...）**
- **Soot相关**
- **集成化/仪器化**

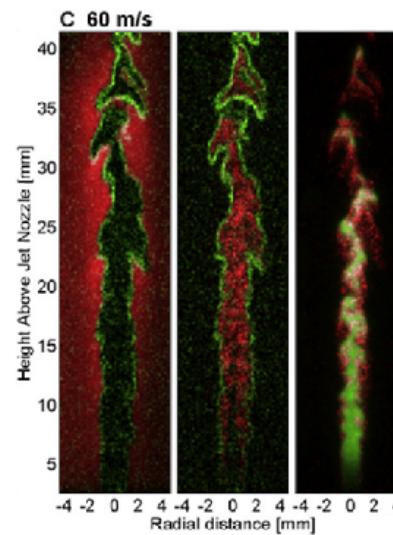
多场多组分



Barlow et al. PCI 35 (2015) 3765–3772



Alden et al. PCI 34 (2013) 1475–1482



多场多组分

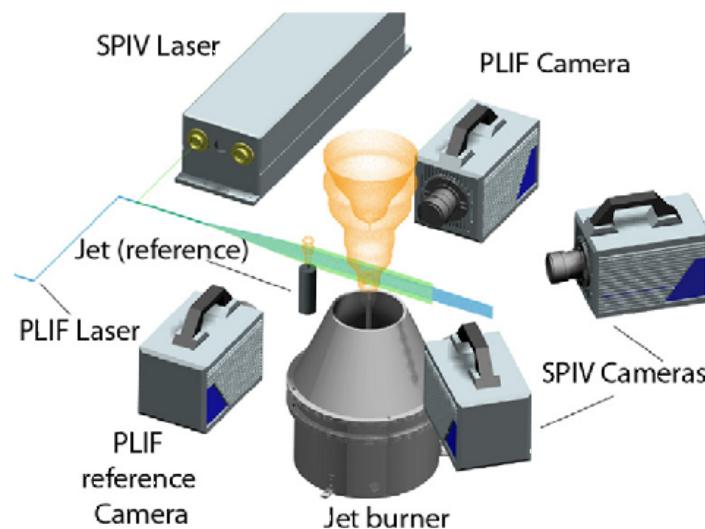
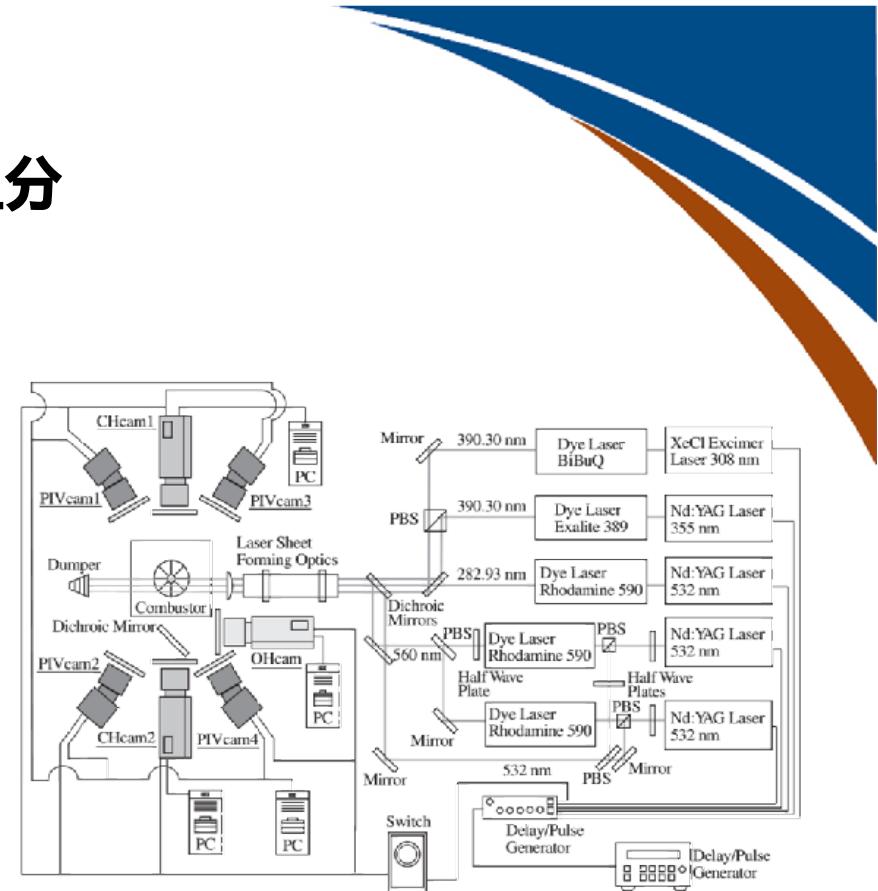


Fig. 1. Experimental setup.

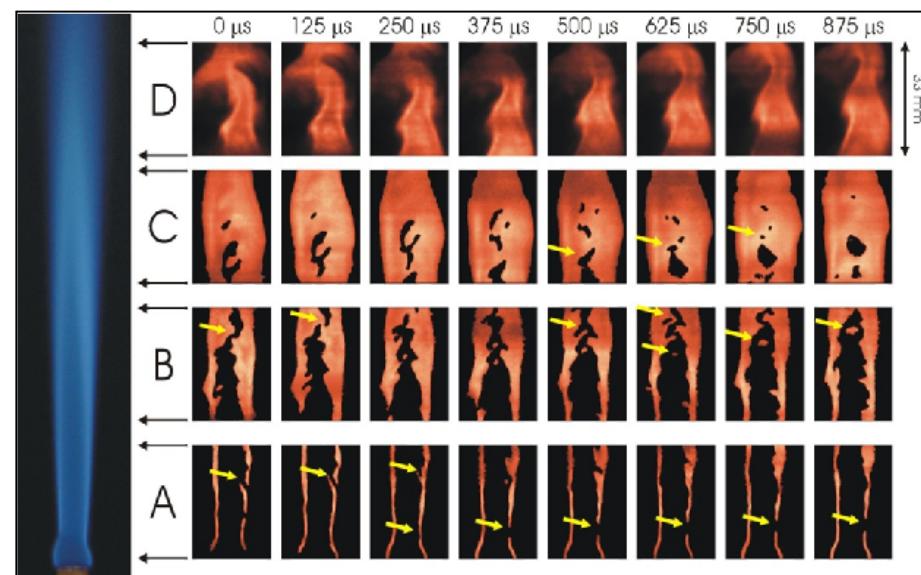
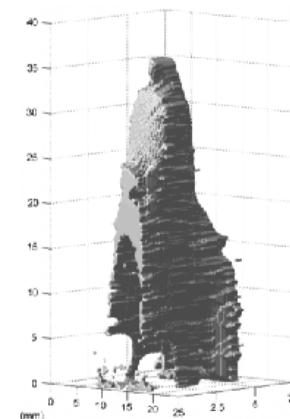
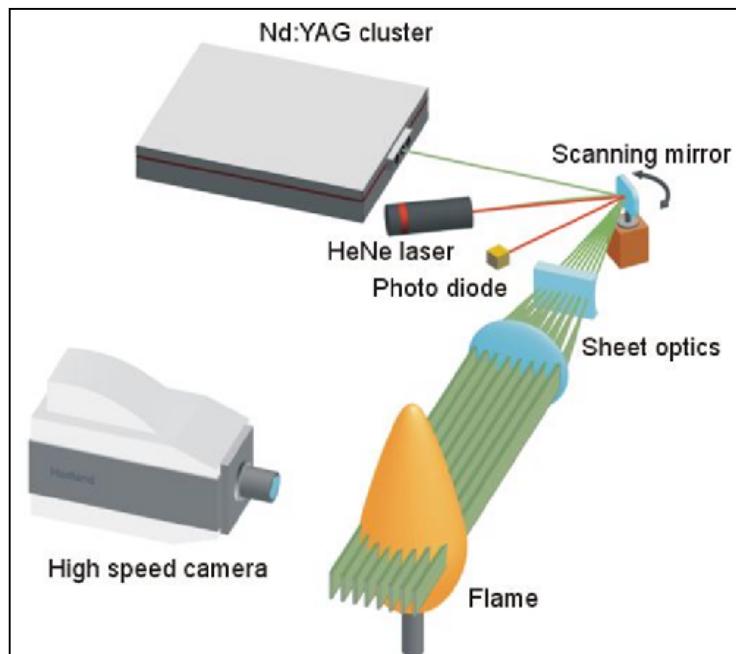
Dreizler et al. PCI 35 (2015) 3773–3781



Tanahashi et al. PCI 33 (2011) 775–782

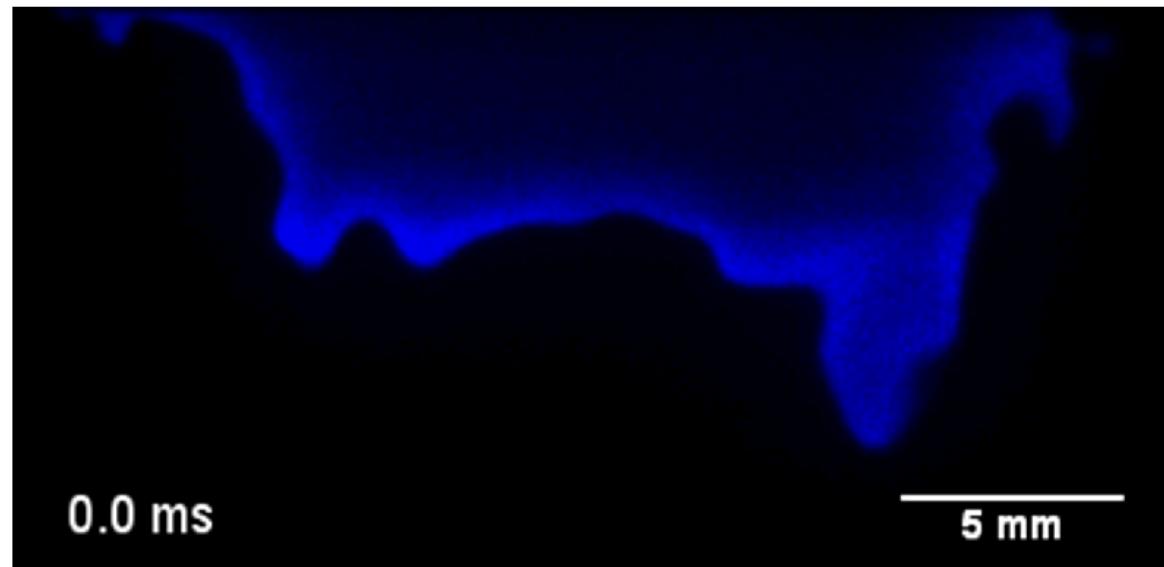
高速/3D

- **Multi-YAG laser system, Lund**



高速/3D

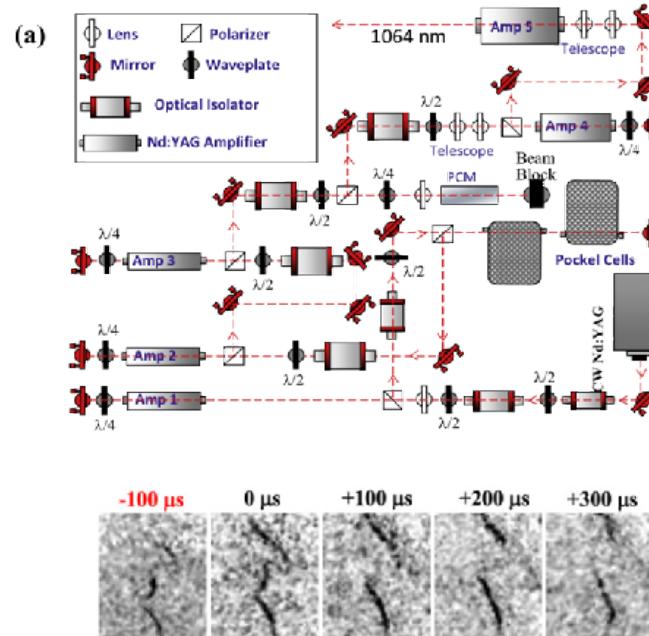
- **Edgewave Kilo Hz laser system**



Alden, Lund

高速/3D

- **QuasiModo Mega Hz laser system**



Lempert et al. PCI 33 (2011) 767–774



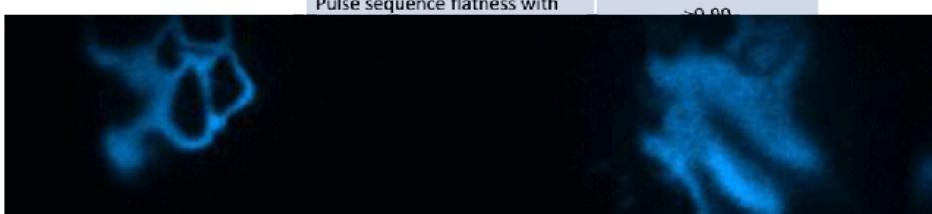
5100 Springfield Street, Suite 301
Dayton, OH 45431-1261
Phone: 937-256-7733, Fax: 937-256-7702
E-mail: contact@spectralenergies.com

Laser Products

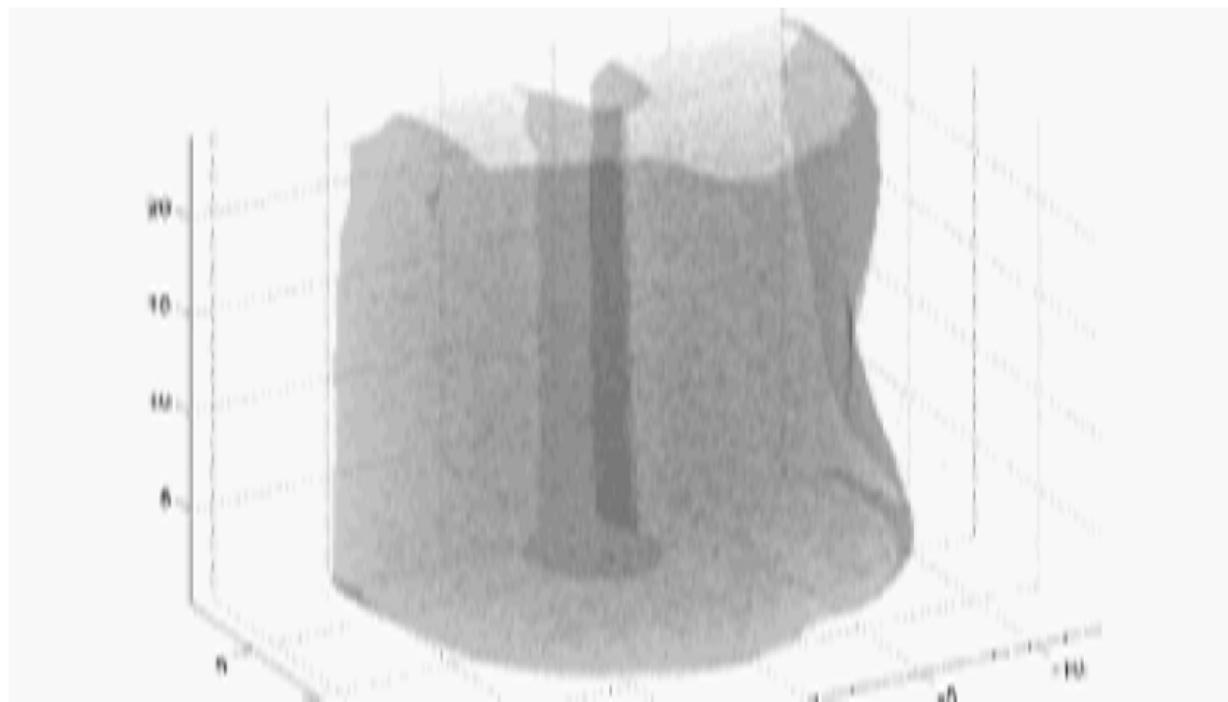
Flashlamp/Diode-pumped Nd:YAG-based master oscillator power amplifier



Specification Sheet	
Individual pulse width	12-15 ns
Pulse frequency within a pulse sequence ⁽¹⁾	2-100 kHz
Maximum pulses in pulse sequence	100 @ 10 kHz 1000 @ 100 kHz
Duration of pulse sequences ⁽¹⁾	1-10 ms
Typical pulse energy ⁽¹⁾ - 1064 nm @ 10 kHz	0.12-1.2 J/pulse
- 532 nm ⁽²⁾ @ 10 kHz	60-600 mJ/pulse
- 355 nm ⁽²⁾ @ 10 kHz	30-300 mJ/pulse
- 266 nm ⁽²⁾ @ 10 kHz	10-100 mJ/pulse
Time between pulse sequences	8 seconds
Spectral Bandwidth	< 1 GHz
Beam diameter, 1/e ²	4 - 7 mm
Beam quality, M ²	< 3
Pulse sequence flatness with	>0.99



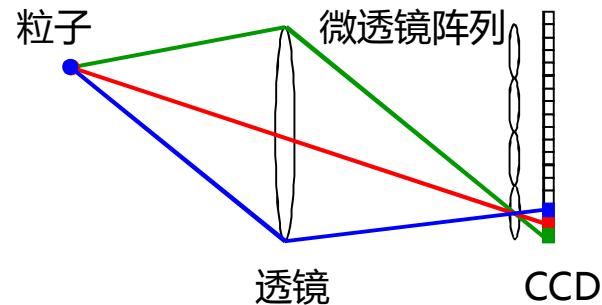
4D



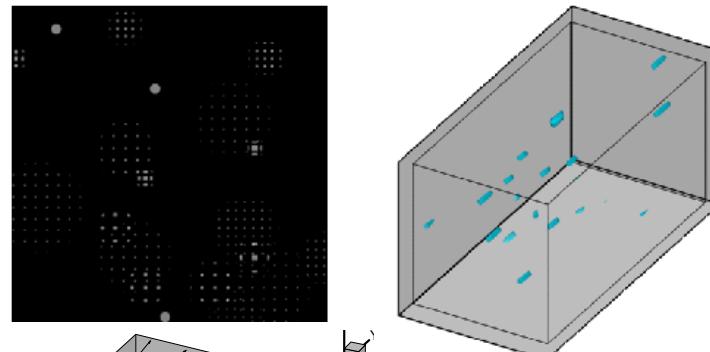
Alden et al. Optics Express, 2011

光场相机

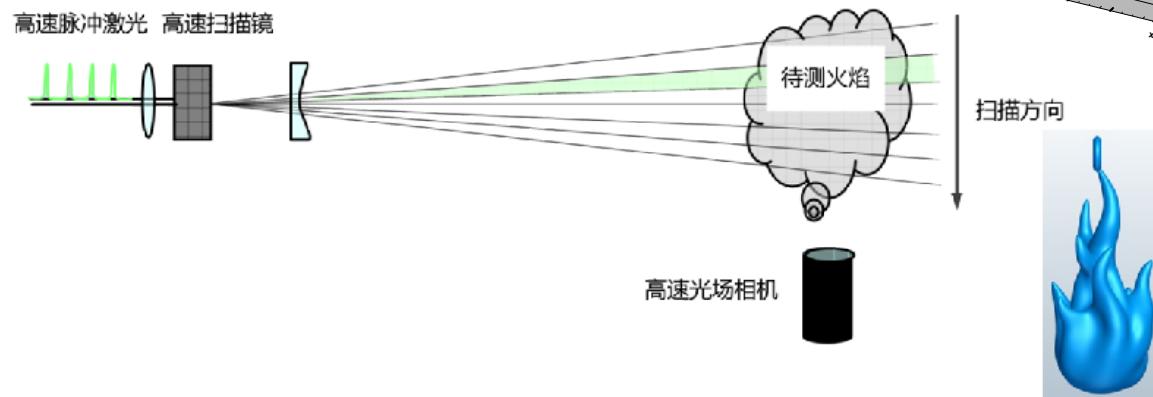
- 光场单相机三维成像原理



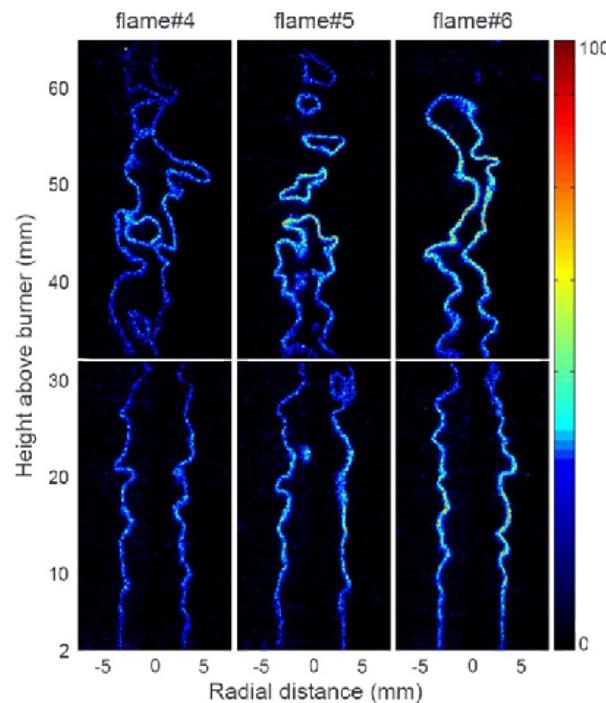
- 光场PIV粒子图像及三维速度场



- 单相机三维LIF测试技术



“新” 组分测量

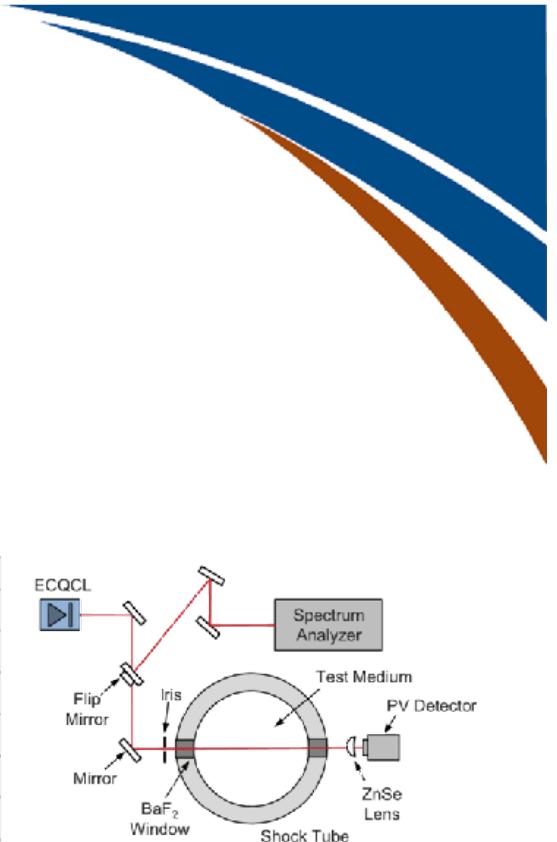
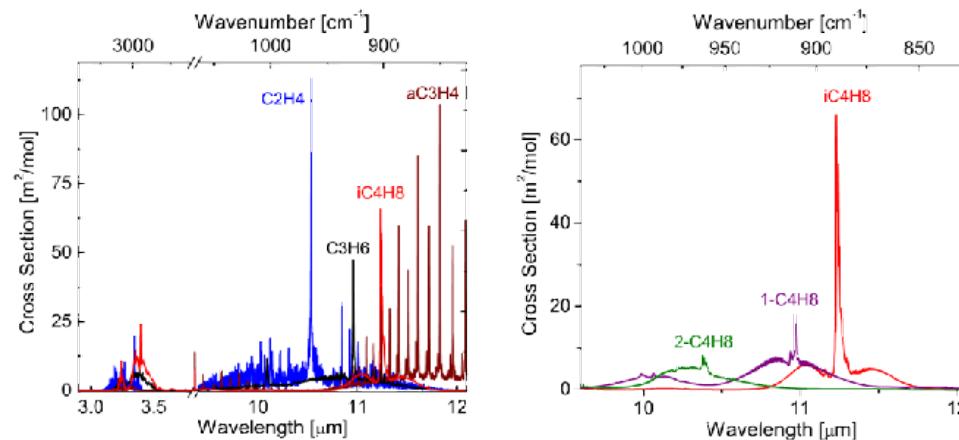


火焰中 CH_3 单脉冲检测
李博 et al. CNF, under review

“新” 组分测量

- 红外 quantum cascade laser

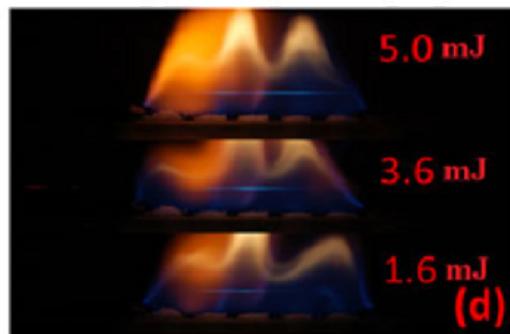
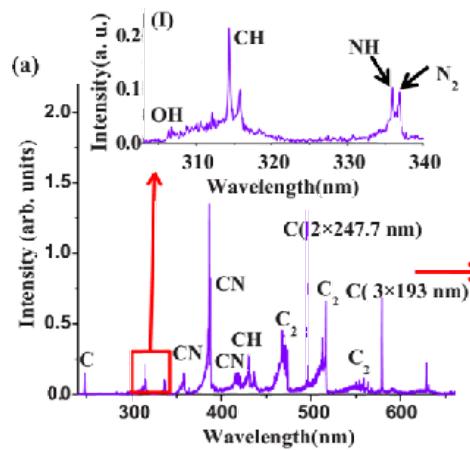
Wavelength:
11.3 μm



Hanson, PCI 35 (2015) 3645–3651

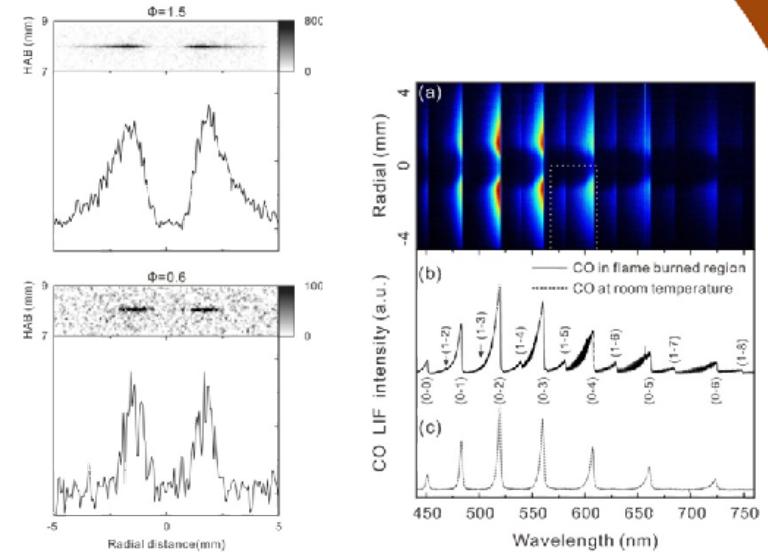
“新” 组分测量

- 飞秒激光 (超快光谱)



fs laser filamentation

徐淮良 et al. LPR 9(2015)275-293

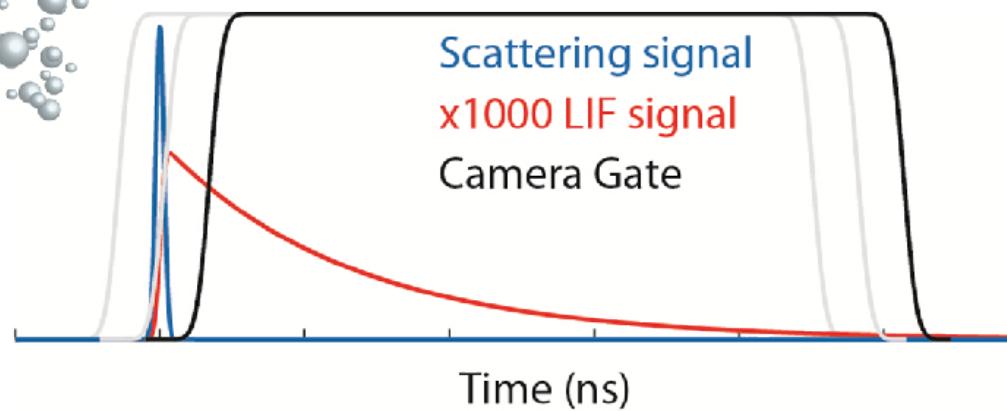
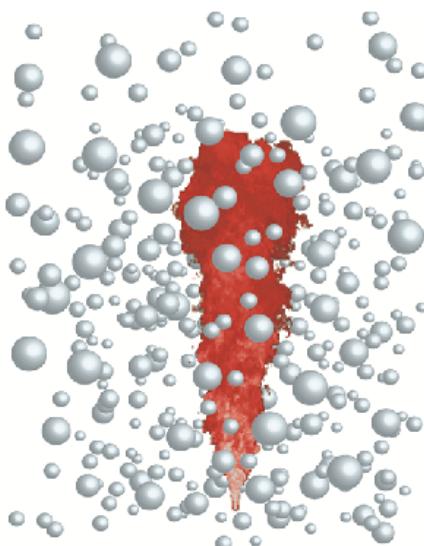


Interference-free fs TPLIF of CO

李博 et al. to be submitted to CNF

恶劣环境：粒子/壁面杂质光

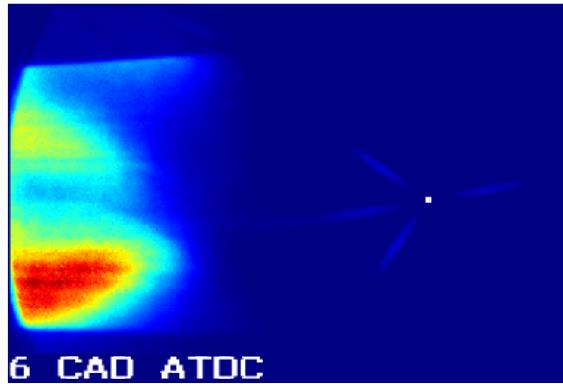
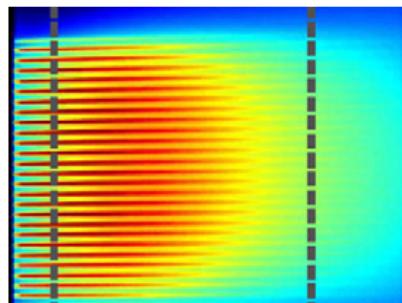
- 时域过滤



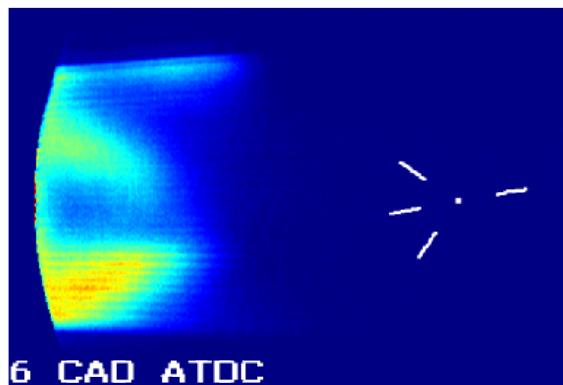
Ehn, Lund

恶劣环境：杂散光

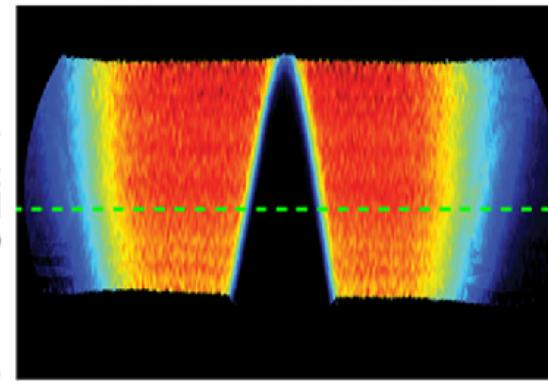
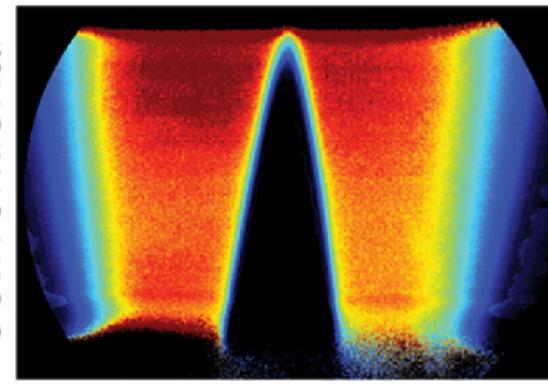
- 空域过滤：SLIPI



Conventional



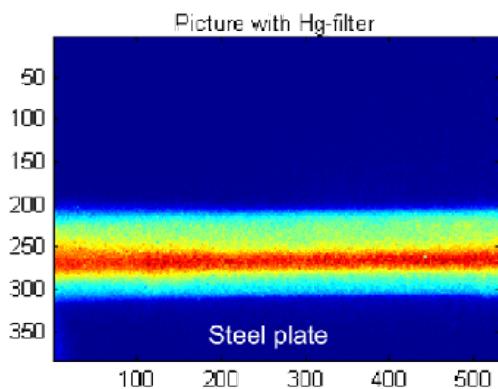
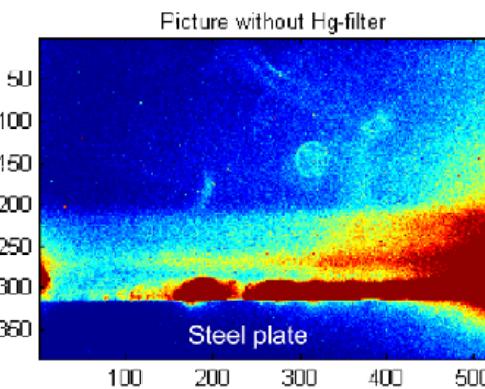
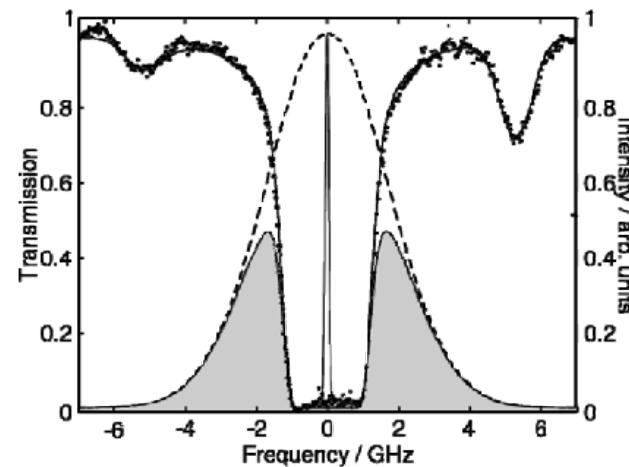
SLIPI



Kristensson et al. PCI 35 (2015) 3689–3696

恶劣环境：杂散光

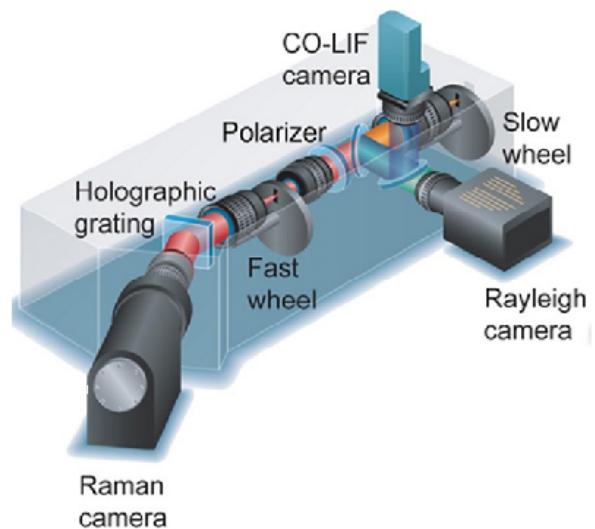
- 谱域过滤：filter Rayleigh scattering



李中山, Lund

恶劣环境：杂散光

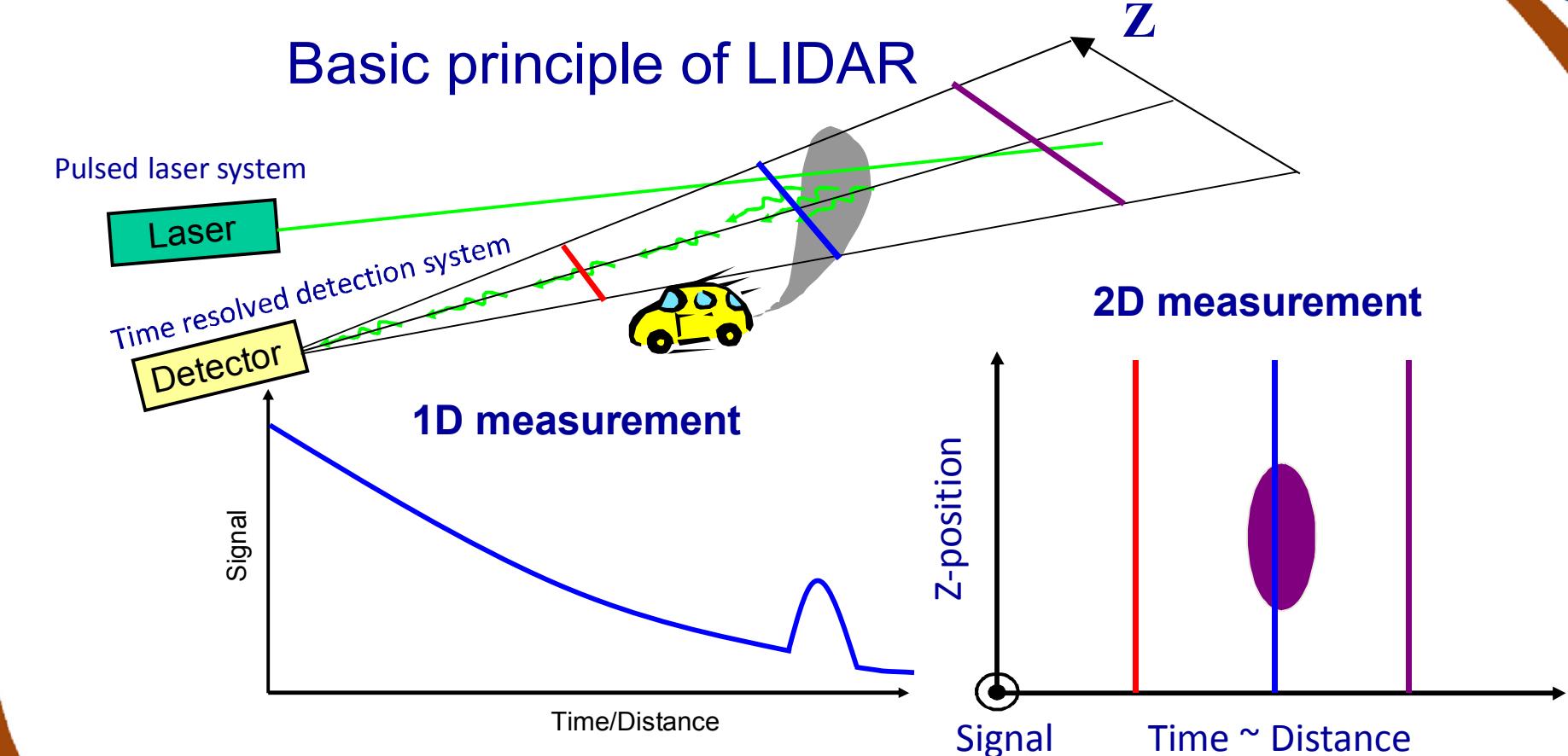
- 偏振过滤



Interference free spontaneous Raman
Barlow et al. PCI 35 (2015) 3765–3772

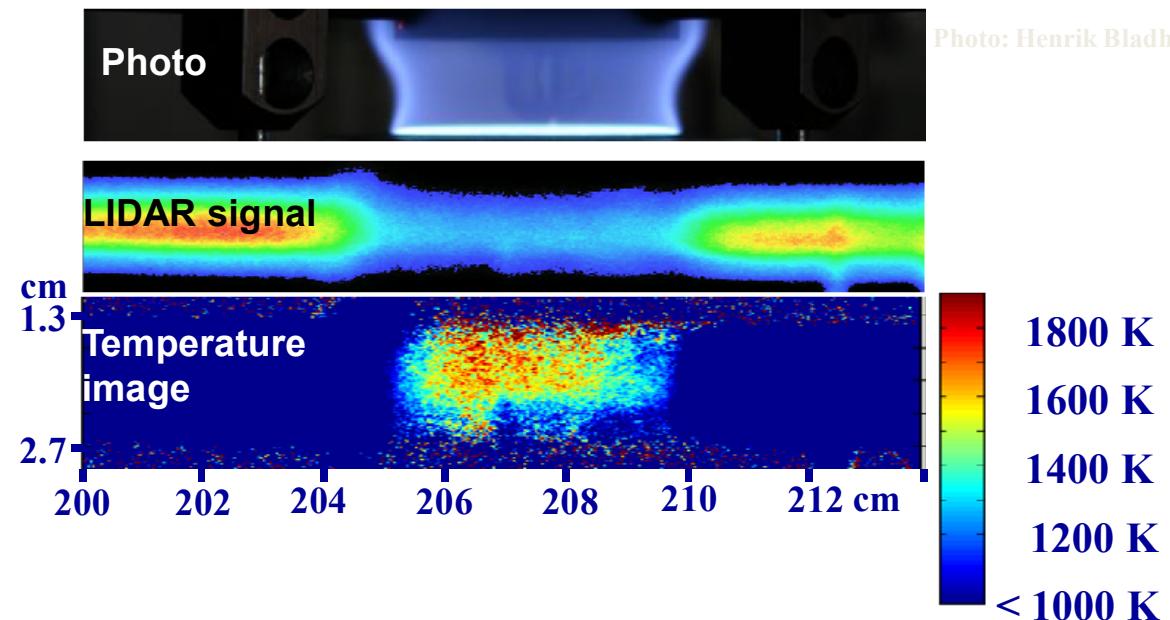
恶劣环境 : limited optical access

Basic principle of LIDAR



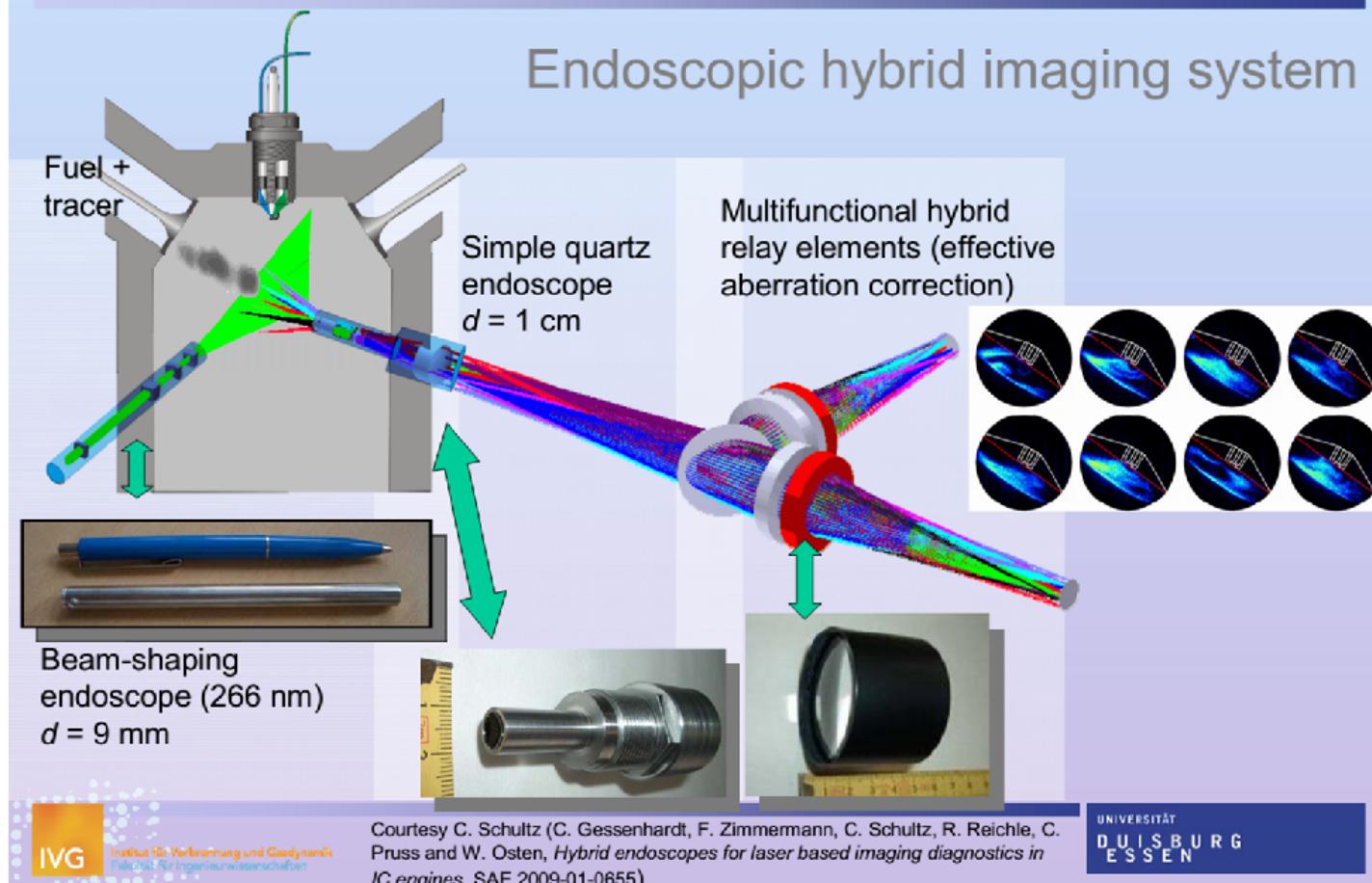
恶劣环境 : limited optical access

- 激光雷达

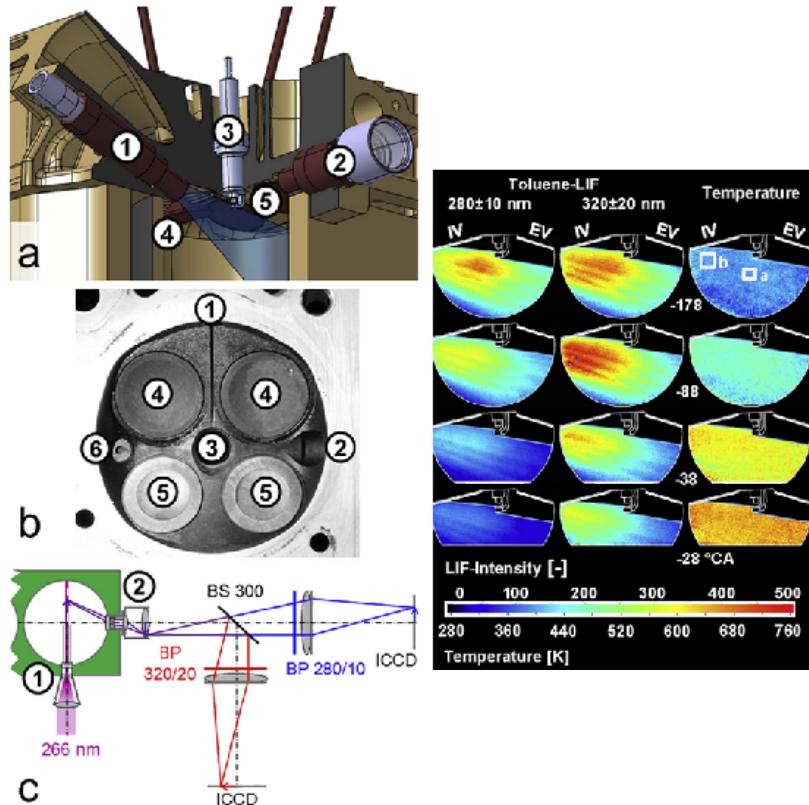


恶劣环境 : limited optical access

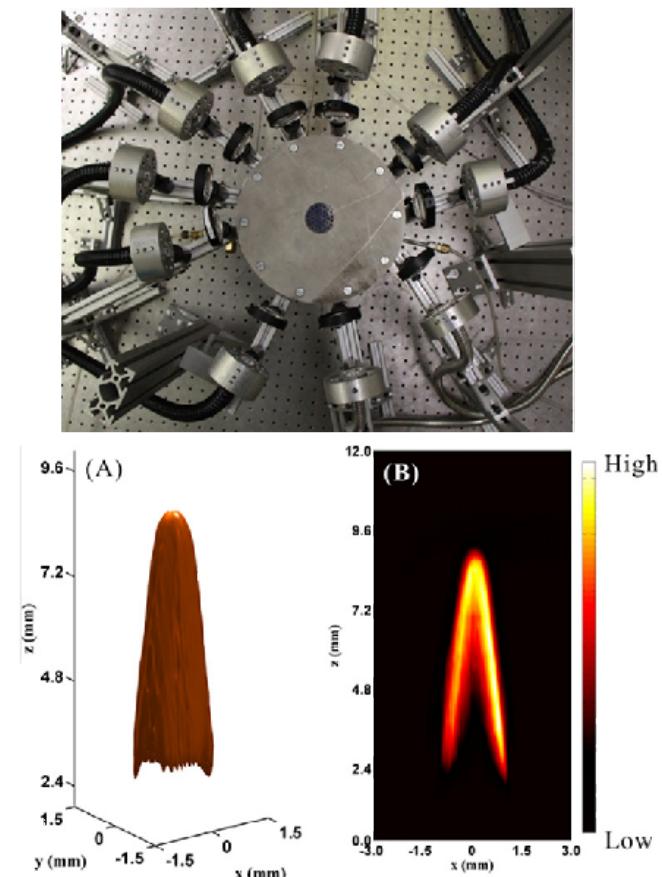
Limited optical access: Engines, gasturbines



恶劣环境 : limited optical access



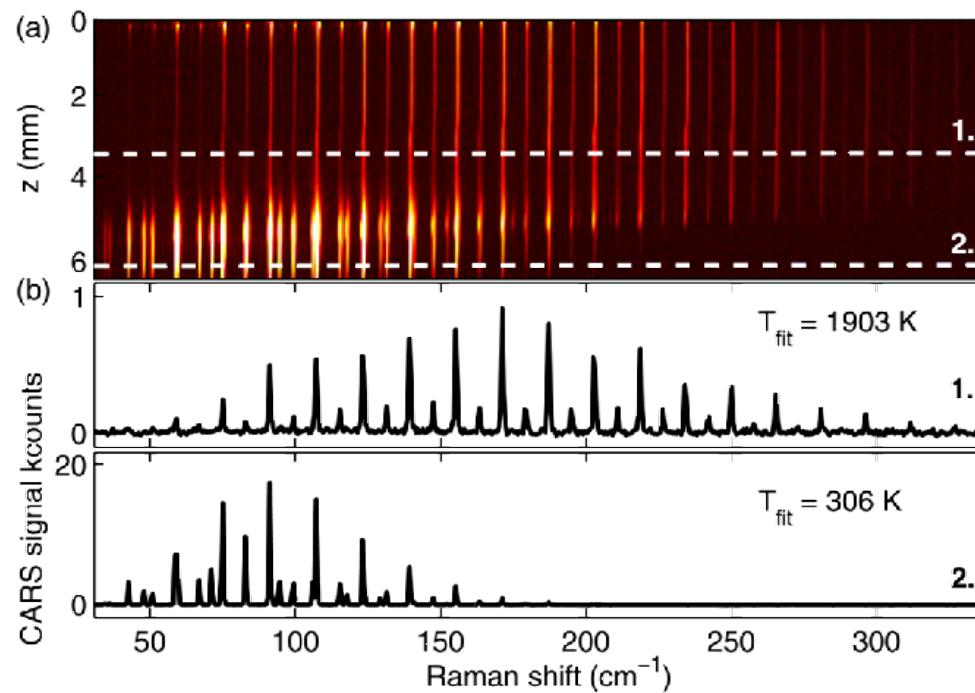
Schulz et al. PCI 35 (2015) 3697–3705



Lin Ma, PCI 35 (2015) 3821–3828

温度测量

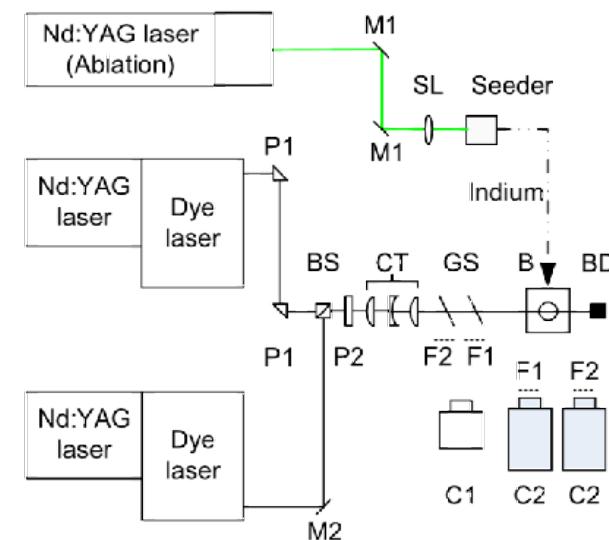
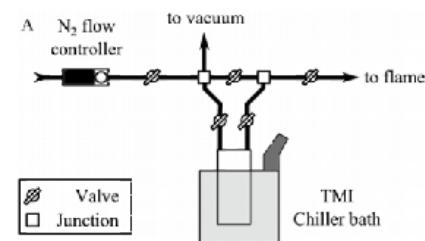
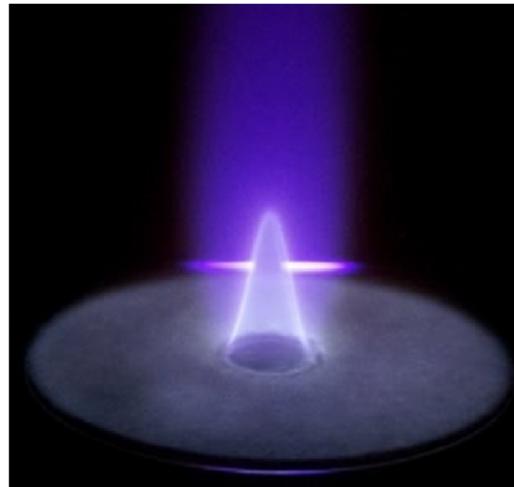
- CARS : 0D → 1D (single-shot ability)



Bolin et al. PCI 35 (2015) 3723–3730

温度测量

- 双线原子测温 : seeding技术发展



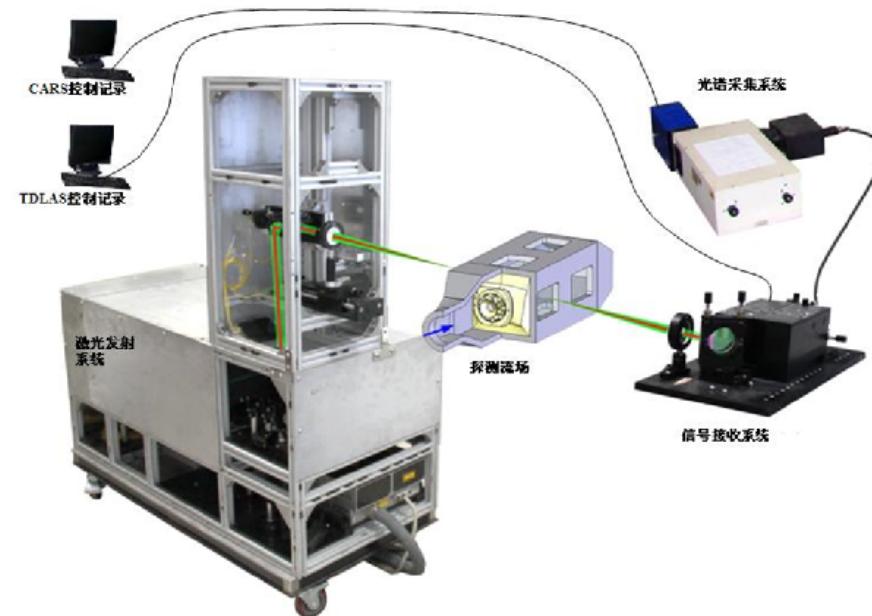
李中山 et al Rev. Sci. Instrum. 86, 093107 (2015) Nathan et al. PCI 34 (2013) 3619–3627

Soot

- **Soot诊断进展：**
 - ✓ 中间产物（例如fs TPLIF of CO）
 - ✓ 温度（双线原子LIF）
 - ✓ Mixture fraction（双光子Kr LIF）
 - ✓ kHz LII（Iowa & Sandia, Applied Optics, 2015）
 - ✓ Combination of LII/Scattering: soot aggregate size（Natl Res Council Canada, PCI 2015）
 - ✓ 时间分辨LII（Adelaide, PCI 2015）
 - ✓ 最小尺寸soot探测，1-1.5 nm（Lund, PCI 2015）
 - ✓ Volume fraction（phase-selective LIBS, 清华, PCI 2015）
- **挑战性课题（尚待解决）：**
 - ✓ 中间产物PAH、原子H量化测量
 - ✓ Mixture fraction测量

集成化/仪器化

- 西北核技术研究所胡志云-CARS系统
- 吉林大学徐淮良-重大仪器设备专项

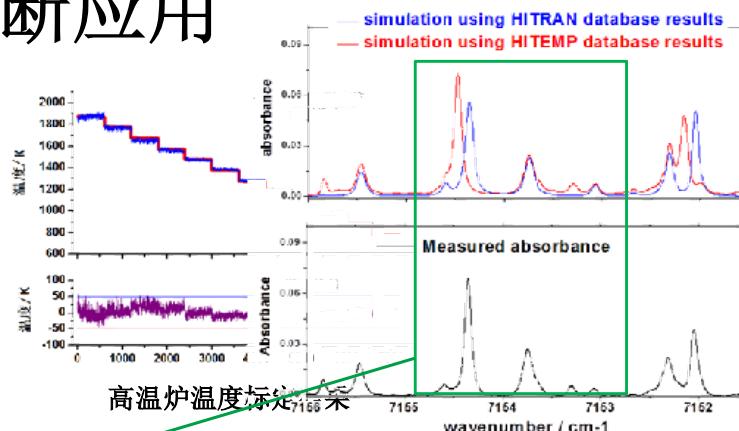


TDLAS燃烧流场诊断应用

已开展研究工作

□ 光谱数据库谱线参数校准

基于加热式高温炉“恒温”平台, 谱线参数标定, 为光谱反演提供准确参数

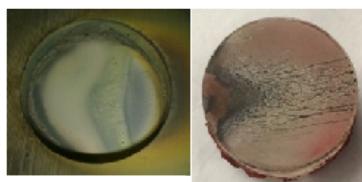


□ 场分布重建研究

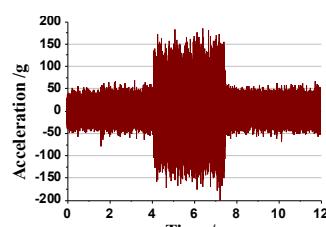
少投影角度/射线下分布重建

□ 工程应用环境适应性

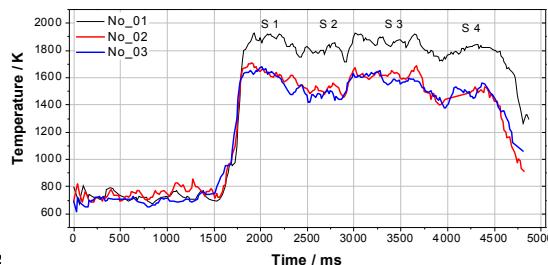
高温、辐射、振动、湍流测量环境下, TDLAS系统集成化、适应性及可靠性, 有效获取光谱



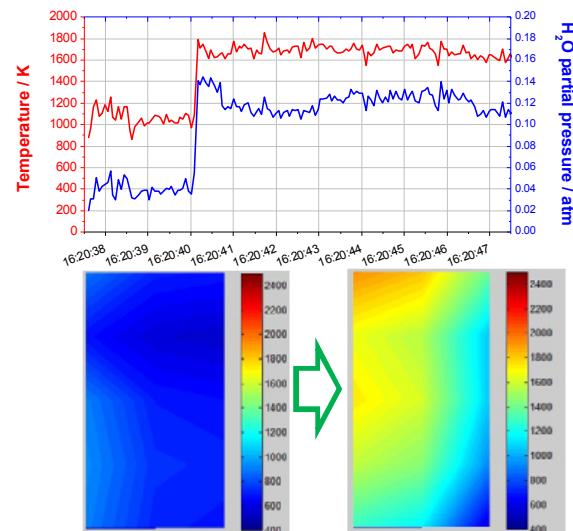
高温/高速气流
(窗片烧蚀&污染)



振动 (及声冲击)



燃烧室出口典型测量结果



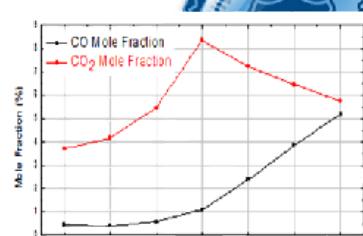
尾喷管温度分布 (1) 加热器启动 (2) 发动机燃烧



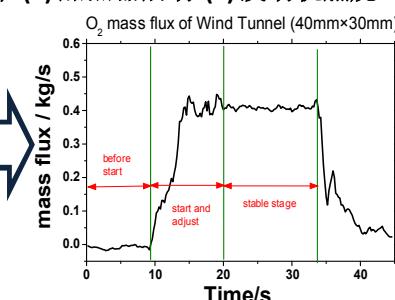
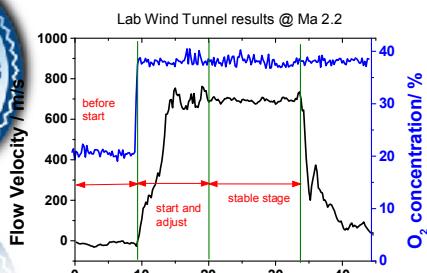
体积20×10×4cm³
质量2kg, 功耗8W



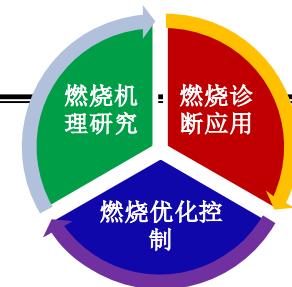
发射/接收探头



内燃机燃烧及尾气排放国家重点实验室
平焰炉不同当量比组分浓度



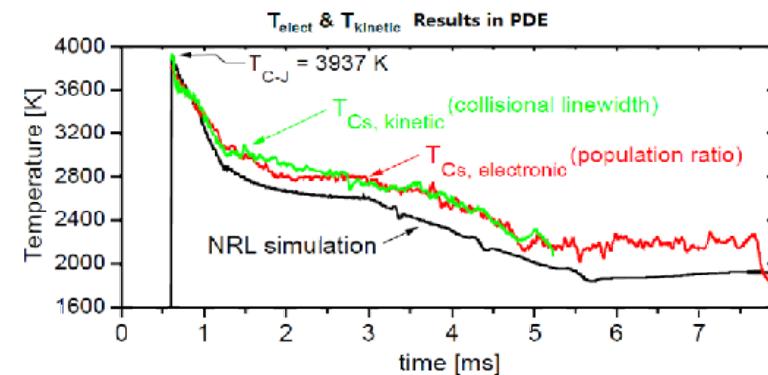
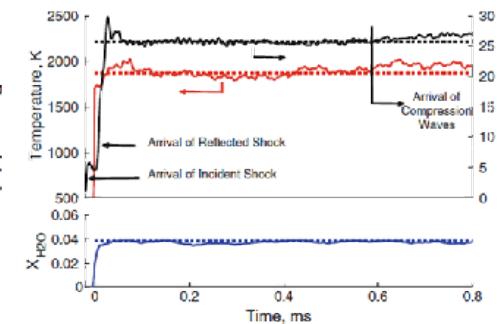
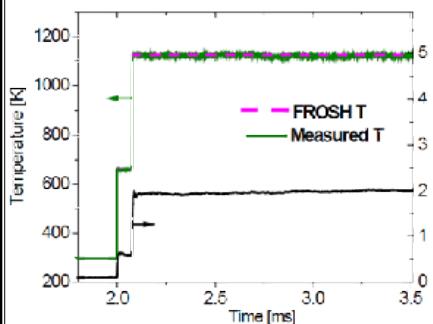
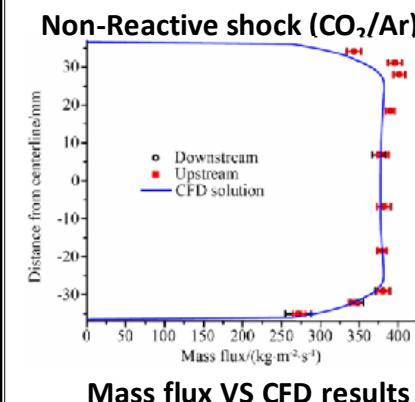
实验室风洞平台试验段质量流量测量 (残余空气、启动、稳定、结束)



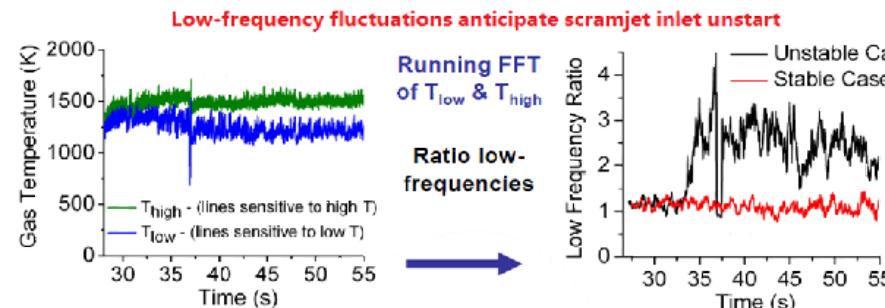
国内外研究进展

➤ 燃烧机理

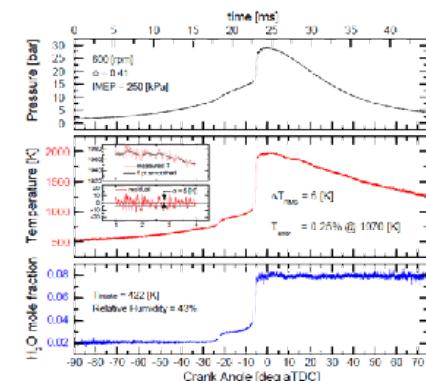
- T、V、H₂O、CO₂、CO、O₂、NO_x、CH₄、C₂H₂ ...
- 燃料分解速率
- 燃烧稳定性、均匀性研究
- CFD模型比对

T_{kinetic} (谱线展宽)、T_{electronic} (能级分子布局比例)对比

Mass flux VS CFD results



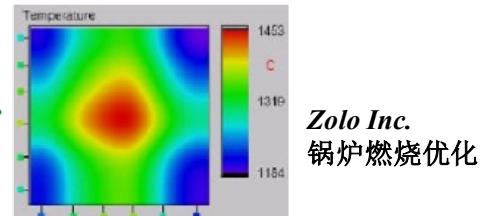
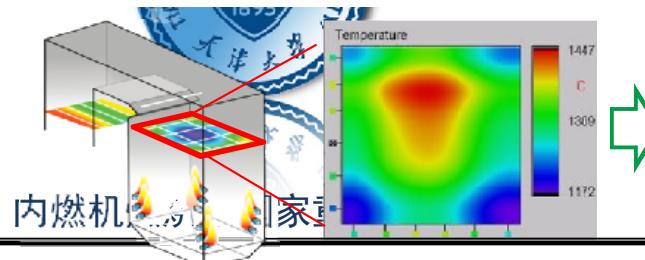
不同温度敏感段吸收线对测量温度低频成分差异指示流场非均匀性

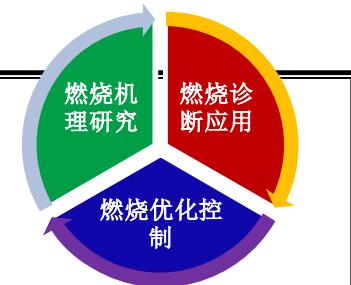


高压环境下, IC 测量结果

➤ 燃烧优化控制

- 过氧量、排放控制 (SO₂、NO_x)
- 锅炉燃烧偏心调制 (防止炉膛结焦)
- 发动机和飞机结冰预警

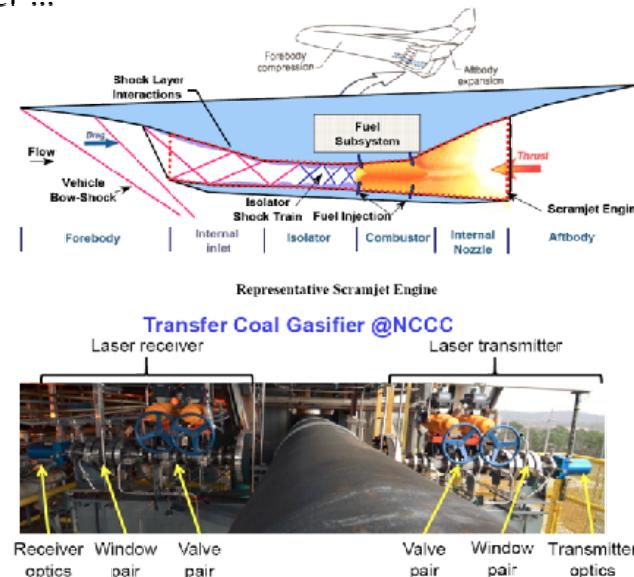
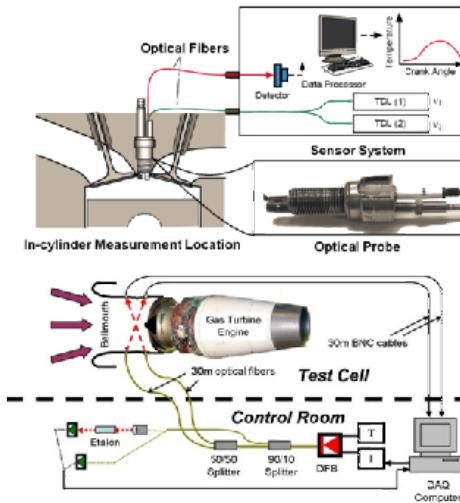
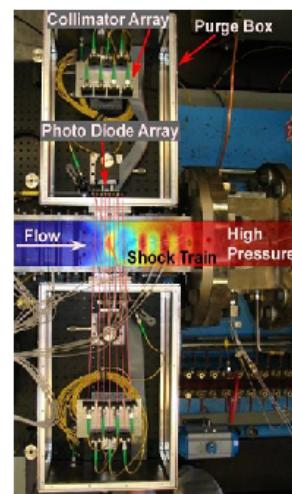
Zolo Inc.
锅炉燃烧优化



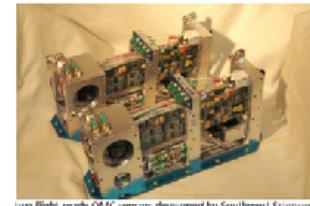
➤ 燃烧诊断应用

- 平焰炉、swirl burner、激波管、冷流风洞...
- Scramjet、turbine、HCCI、PDE、IC engine ...
- Coal fired Power plant/furnace/boiler、Coal Gasifier ...

国内外研究进展



TDLAS 系统封装 (HIFiRE)



SWS, 1.8kg, P=2W



Zolo, 2.5kg, P<13W

发展方向与难点

TDLAS——T、V、P、X, 2D以及衍生

□ 多技术融合, 燃烧模型和机理研究

TDLAS+LIF+CARS+..., 燃烧过程状态、产物及中间产物检测

□ 燃烧状态诊断以及控制

高时间分辨测量参数特征量提取, 表征燃烧状态/问题, 指导诊断和控制措施

□ 高压燃烧流场诊断

高压燃烧流场 (压力范围大、波动), 工程应用下可靠检测 (航发燃烧室、内燃机)

□ 非平衡态研究

动力学温度、振转温度、电子学温度

□ 断面二维高分辨重建

少投影高时间分辨 (超光谱重建), 重建结果比较评估 (CFD模型校验)

□ 机遇

UV、中红外光源 (QCL、ICL), 更多的选择

煤燃烧诊断的研究现状

煤燃烧/热解前、后的检测诊断

- 1、煤燃烧/热解的常用反应器包括滴管炉(DTF)、热重分析(TGA)等，反应温度可控，但多在1000度左右；
- 2、用色谱、光谱、质谱等仪器如FTIR、GC、MS、XRF、ICP等对反应前煤粉、反应后烟气和灰渣的组分及其含量进行检测分析；
- 3、可以得到煤的燃烧特性、污染物生成规律、重金属及碱金属的迁移转化等

煤燃烧过程中的检测诊断

- 1、煤燃烧装置主要包括单火嘴实验炉、各种中试煤粉炉及大型锅炉，反应温度可达1500度以上，是脉动的、具有三维特征的气固两相物理化学过程；
- 2、基于煤燃烧火焰自发射光谱分析及可见光火焰图像处理的在线测量诊断技术可以火焰温度分布等，目前是一种主要的分析手段；
- 3、近些年，基于激光的诊断技术，如LIBS、TDLAS、PIV等，开始用于煤粉燃烧的组分、温度、速度的测量中。

煤燃烧诊断的难点、发展及合作

难点：1、在实验室反应器甚至是单火嘴燃烧炉中，通过燃烧诊断得到的规律及结论，有可能不太适用于大型工业燃煤锅炉中；2、由于煤燃烧火焰中含有大量的焦炭、飞灰等微米级颗粒物，使得基于激光的诊断技术在应用中存在困难，尤其是在大型燃煤锅炉中。

发展：1、发展对火焰自发射光谱/图像的分析技术，从中同时得到煤燃烧火焰的温度分布、颗粒物浓度分布、热辐射分布等更为丰富的信息；2、进一步发展基于激光的燃烧诊断技术，使之能实现对煤燃烧火焰中速度场、组分浓度的精确检测。

合作：1、将火焰自发射光谱/图像分析技术与基于激光的诊断技术相结合，实现对煤燃烧火焰中多种物理量的同时在线检测，用于综合评价各种新型煤燃烧技术的性能；2、针对煤燃烧装置，将燃烧前的煤质分析、燃烧过程中的火焰检测、燃烧后的烟气及灰渣分析相结合，实现对煤燃烧反应动力学、污染物生成、燃烧稳定性的深入理解。

未来合作

- **Sandia : TNF workshop (湍流非预混火焰 , 1996)**
- **Lund : Low swirl burner , high pressure jet flame**
- **Adelaide : soot flame workshop (2012)**
- **DLR : gas turbine combustor**
- ...

欢迎大家批评指正！



内燃机燃烧学国家重点实验室