Real-Time Control of Lean Blow Out Limit in Premixed Combustors for Reduced NO_x Emissions

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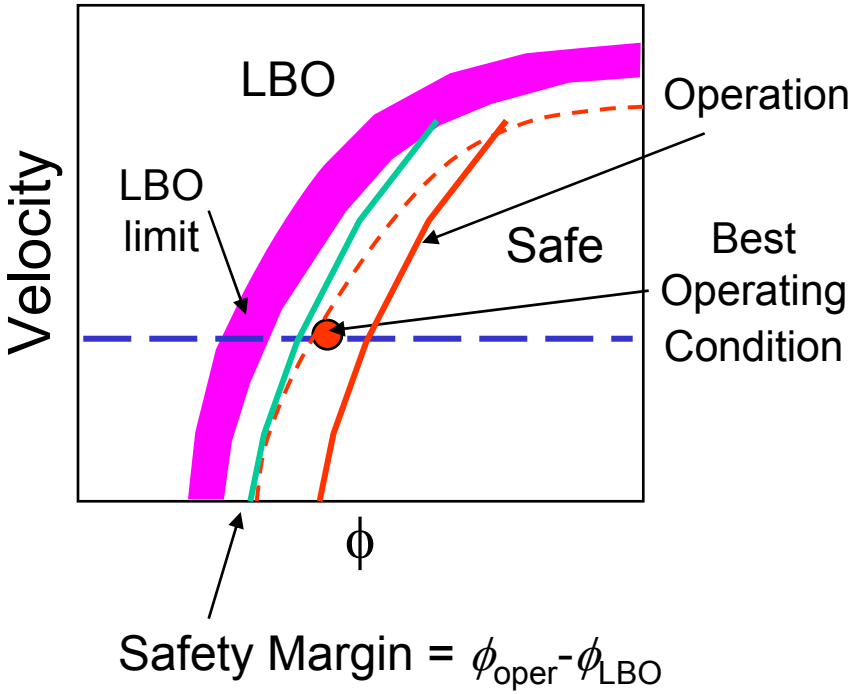
Lean Blow Out (LBO)

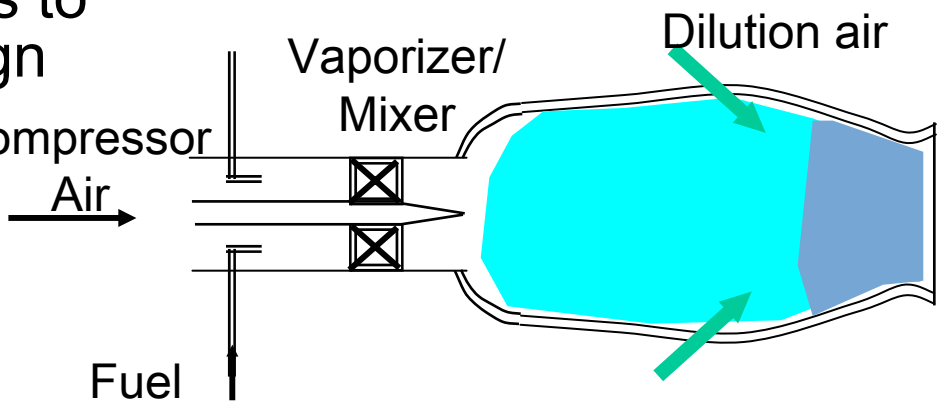
- Low NO_X emissions
  - ➢ Lean
  - – Lean blow out problem
- Current design
  - – Based on worst case scenario
- Better design
  - – Based on normal operation
- Turbine engines
  - – Air fluctuations
  - – Rapid power changes

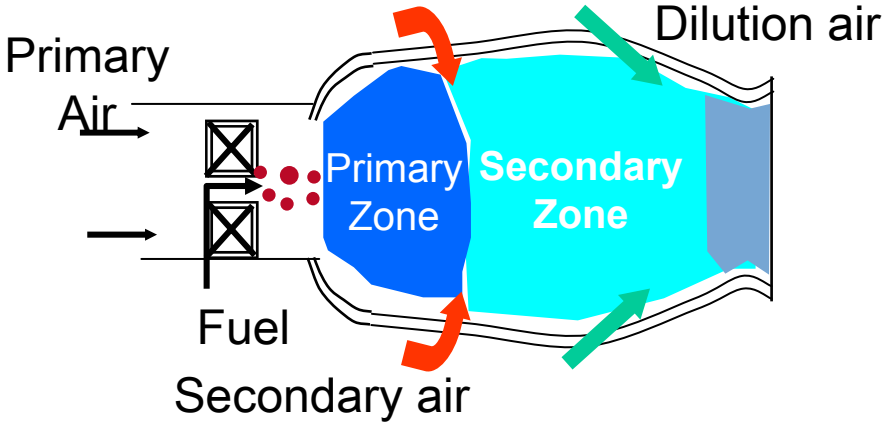


➢ Need: Active LBO control

Rationale for Studied NOx Reduction Approach

- Two **conflicting** approaches to aeroengine combustor design
  - **LPP Combustor**: **lowest NOx but LBO problems**
  - **Conventional Combustor**: **stable operation but high NOx**
- **Can we combine the advantages of both combustor designs?**

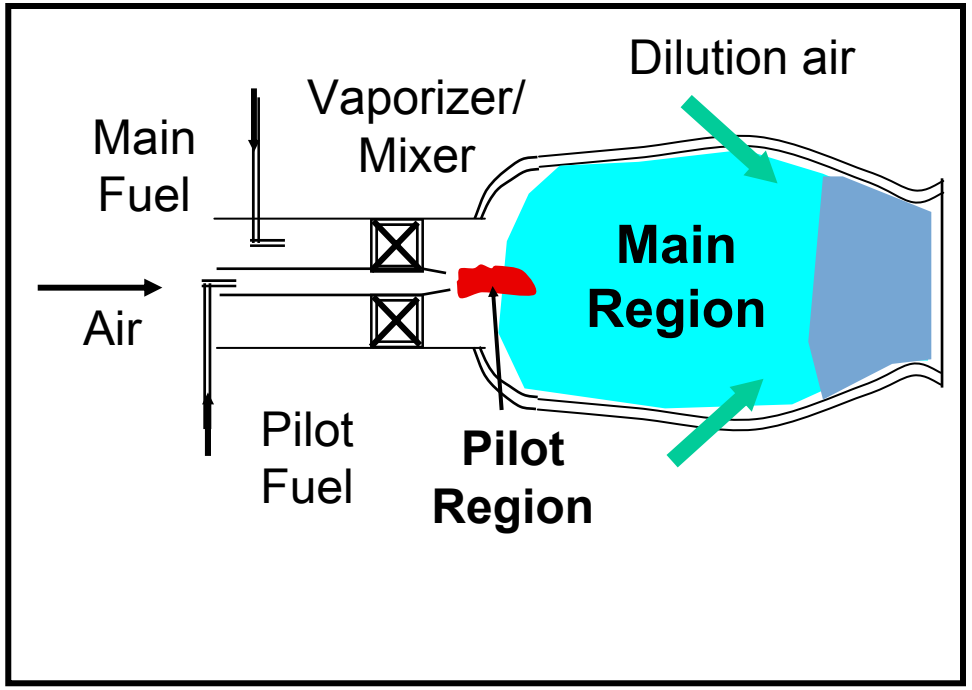




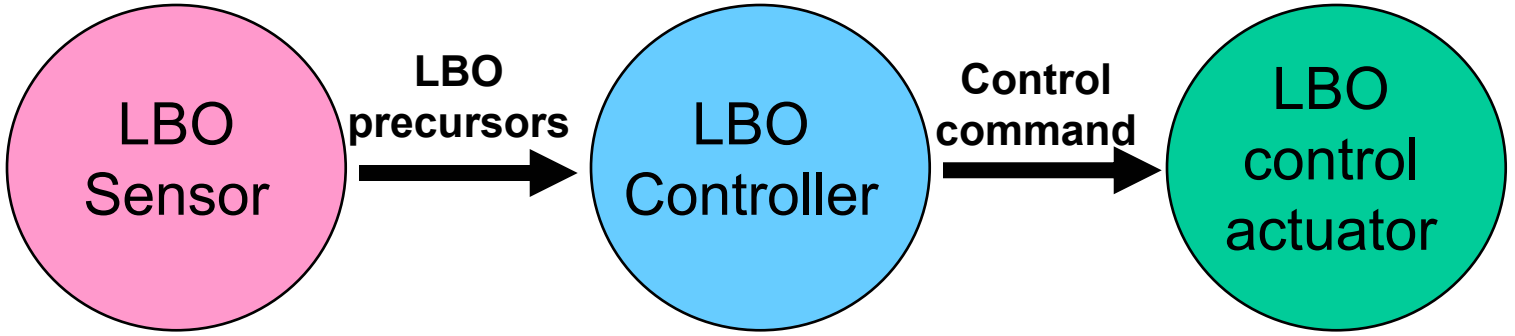
Rationale (con't)

Our approach is to **combine low NOx** and **stability** through **fuel-split control**

- feedback control of fuel sent to lean **main** combustion region and "*less lean*" **pilot** region
- use **minimum fraction of fuel in pilot** region needed to eliminate LBO (potentially zero at some power settings/flight conditions)
- determine **LBO proximity** with optical/acoustic **sensors**
- also improves **safety** during **transient operations**
- **Improves "off design" and "on design" performance**



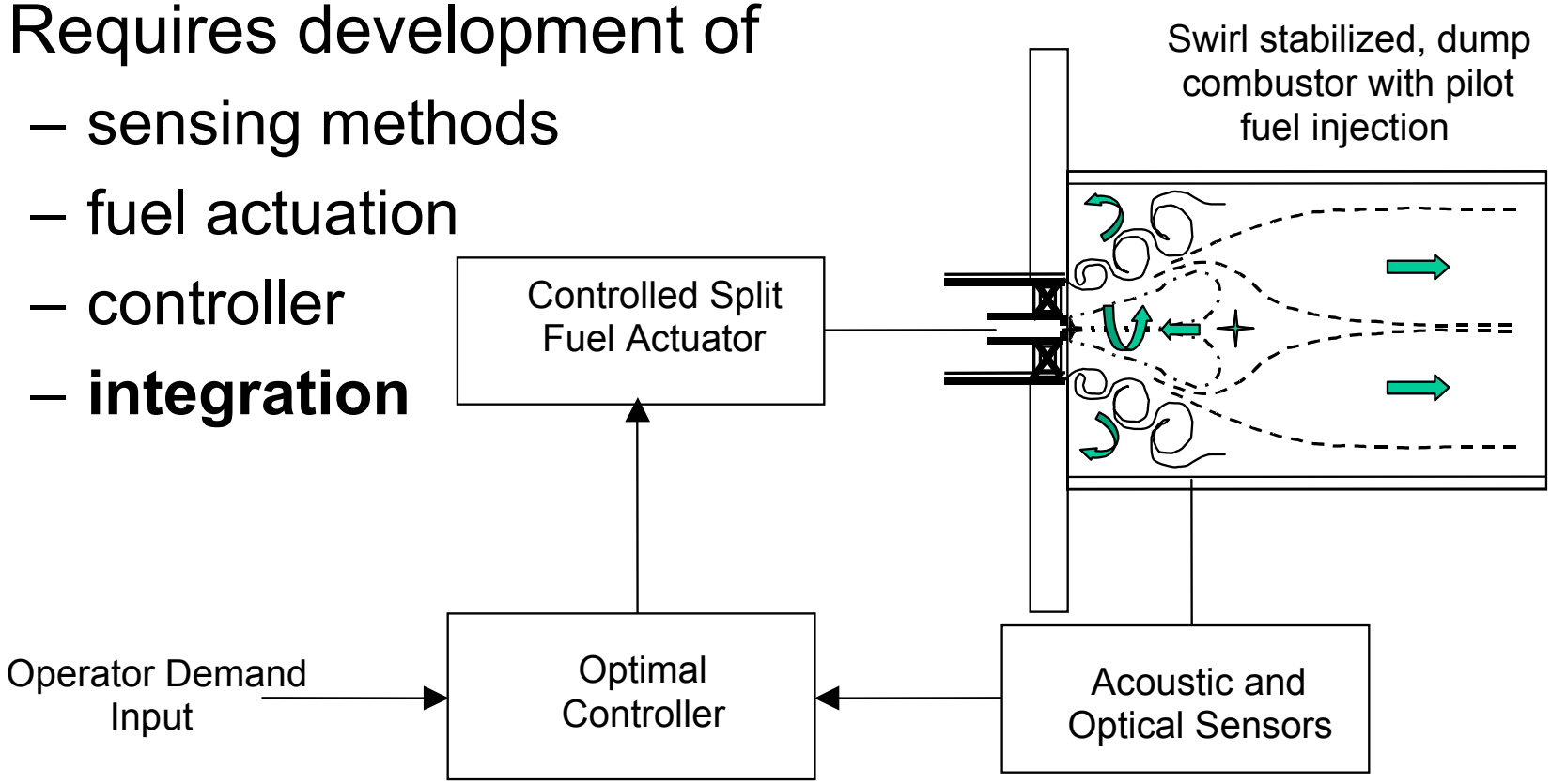
LBO controller



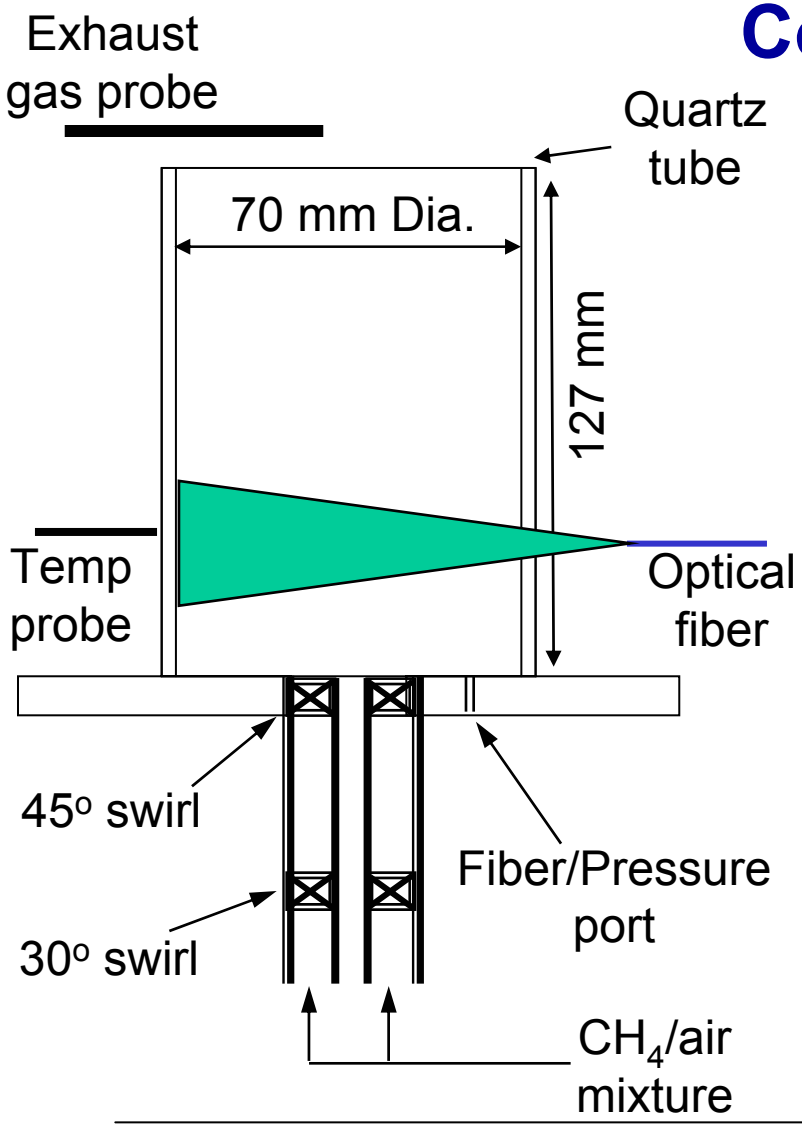
- Detect precursors
  - Product gases
  - Acoustic pressure radiated
  - Chemiluminescence
    - ➢ OH*, CH*, C_2*
- Assess safety
  - LBO proximity parameter
- Optimize performance
  - Minimize NOx
- Control command
- Enhance stabilization
  - Swirl
  - Temperature
  - Redistribute airflow
  - ✓ Redistribute fuel (const. power)

LBO Control System

- Requires development of
  - sensing methods
  - fuel actuation
  - controller
  - **integration**

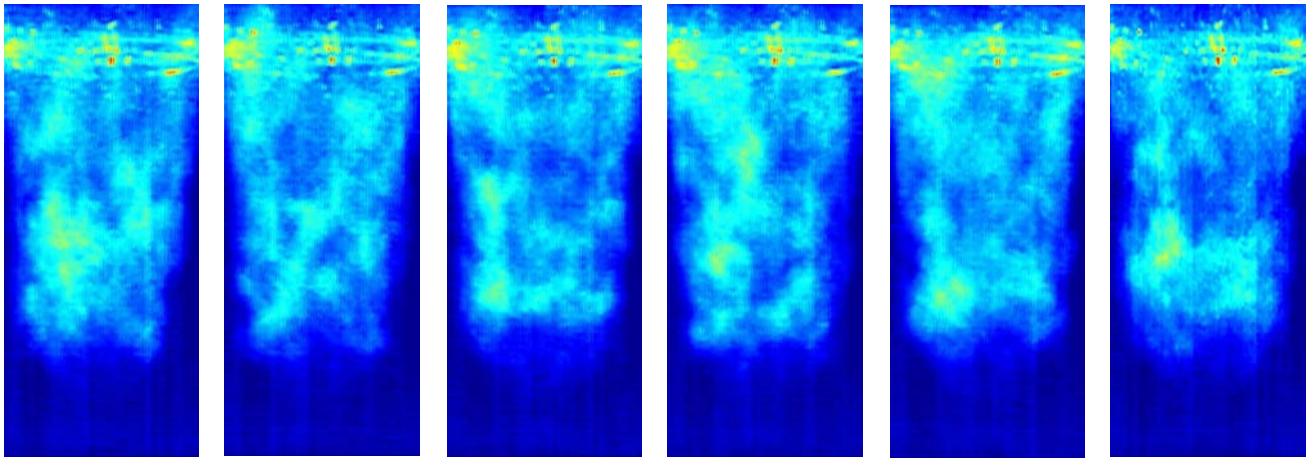


Combustor



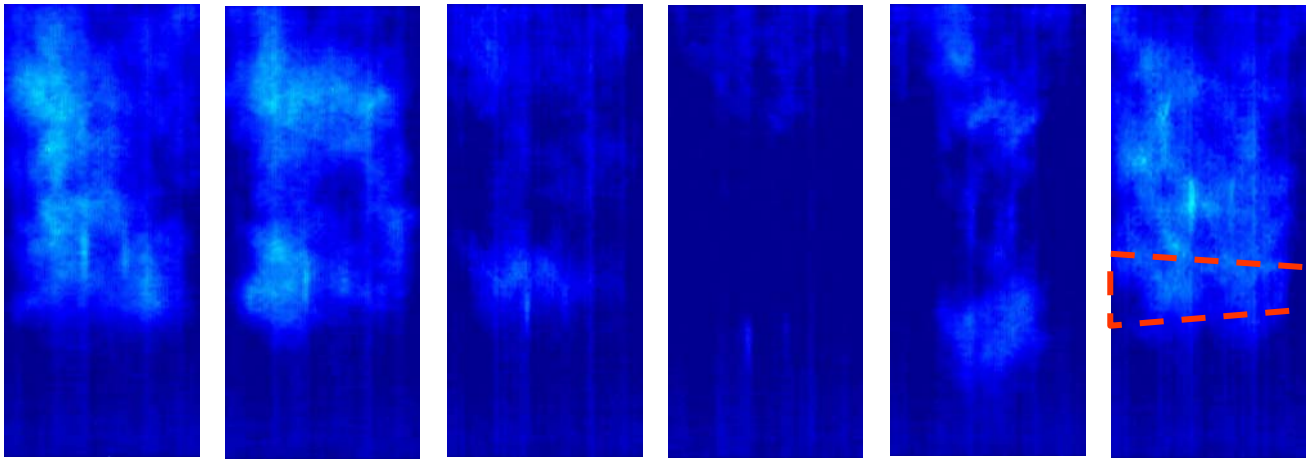
- Air flow ~20 g/s
  - burned gas velocity ~22 m/s
- $T_{outer\ wall}$ = 400-600 K
- $\phi_{LBO} \cong$ 0.75-0.8
- 0.1-0.4 g NO_x/kg fuel

High Speed Visualization



ϕ = 0.79
Δt = 2 msec

Flame zone constant



ϕ = 0.76
Δt = 16 msec

Precursor event

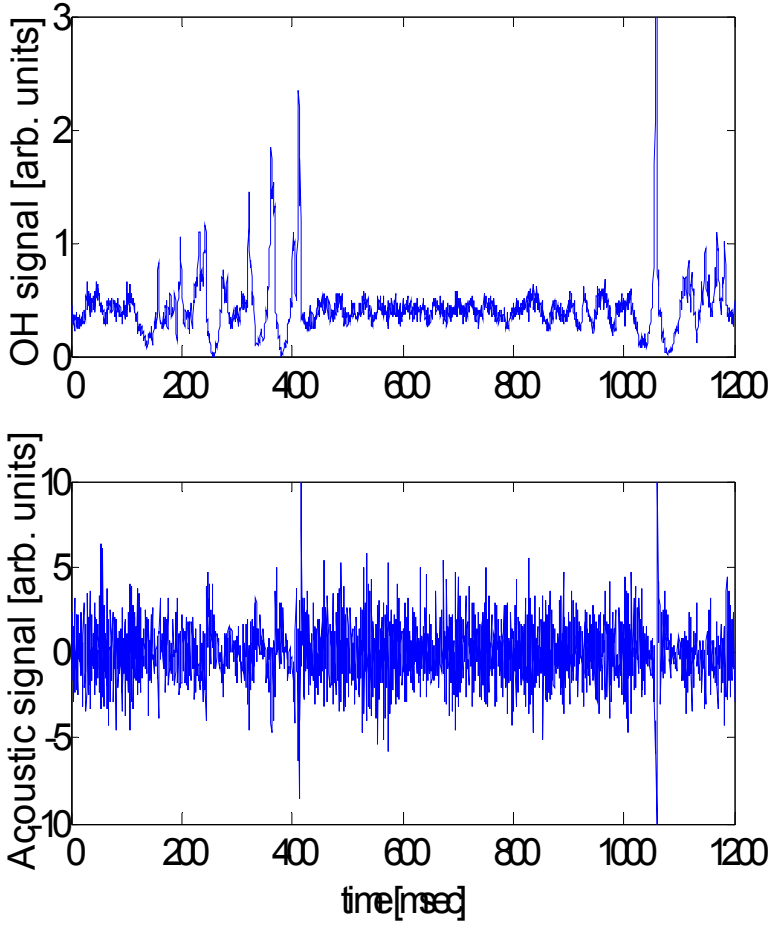
- Extinction and reignition

Sensor Data Analysis Strategies

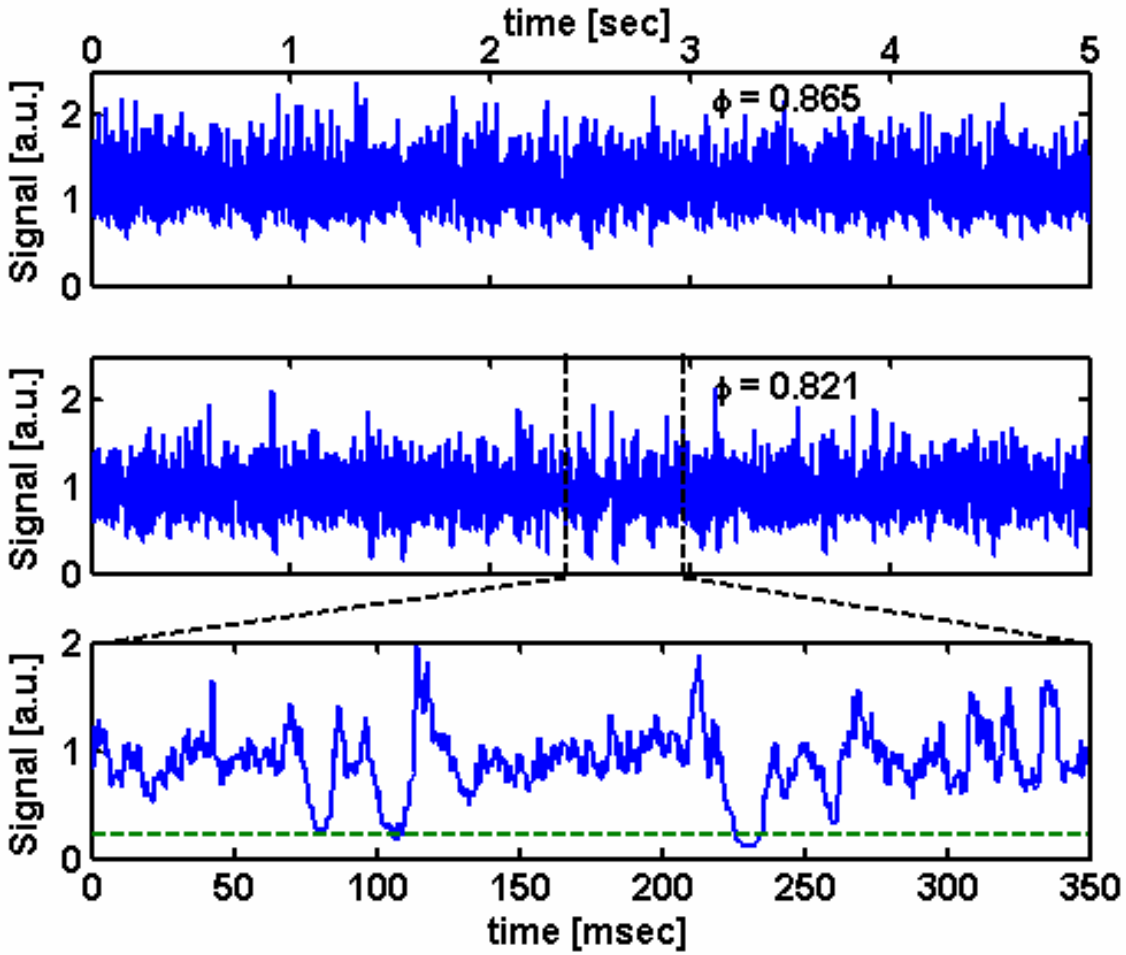
- **Spectral Methods**
- **Thresholding/Min-Max Methods**
  - Detect large deviations in signal value (e.g., extinction-ignition)
- **Statistical Methods**
  - e.g., n'th statistical moment:

$$\frac{1}{T}\int_{t=0}^{T}(p'(t)-\bar{p})^{n}\,dt$$

  - Detect changes in signal statistics
  - Higher order moments more sensitive to intermittent events



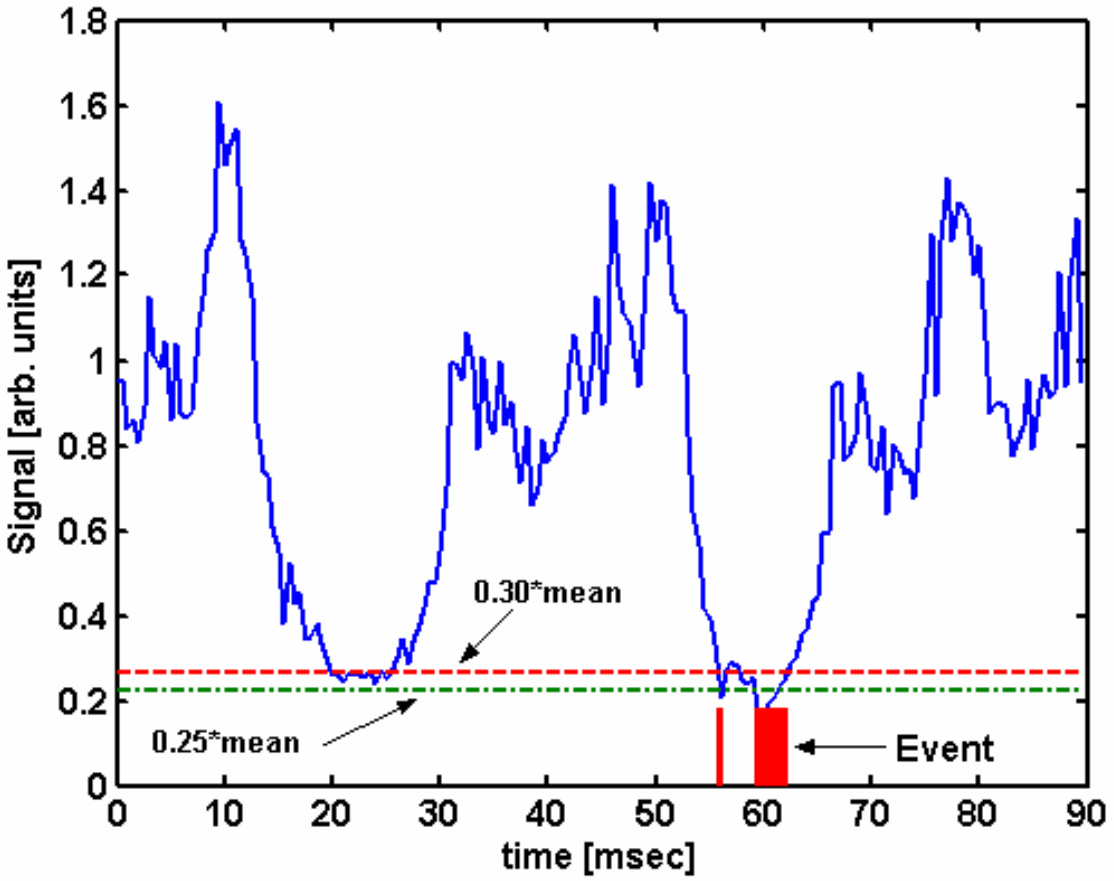
OH Emission Near LBO



- Average intensity increases with ϕ
  - can't use absolute signal approach
- Short bursts at random(?) times
- Extinction events
  - low signal
  - long duration
  - not always followed by ignition spike

  ➢precursor

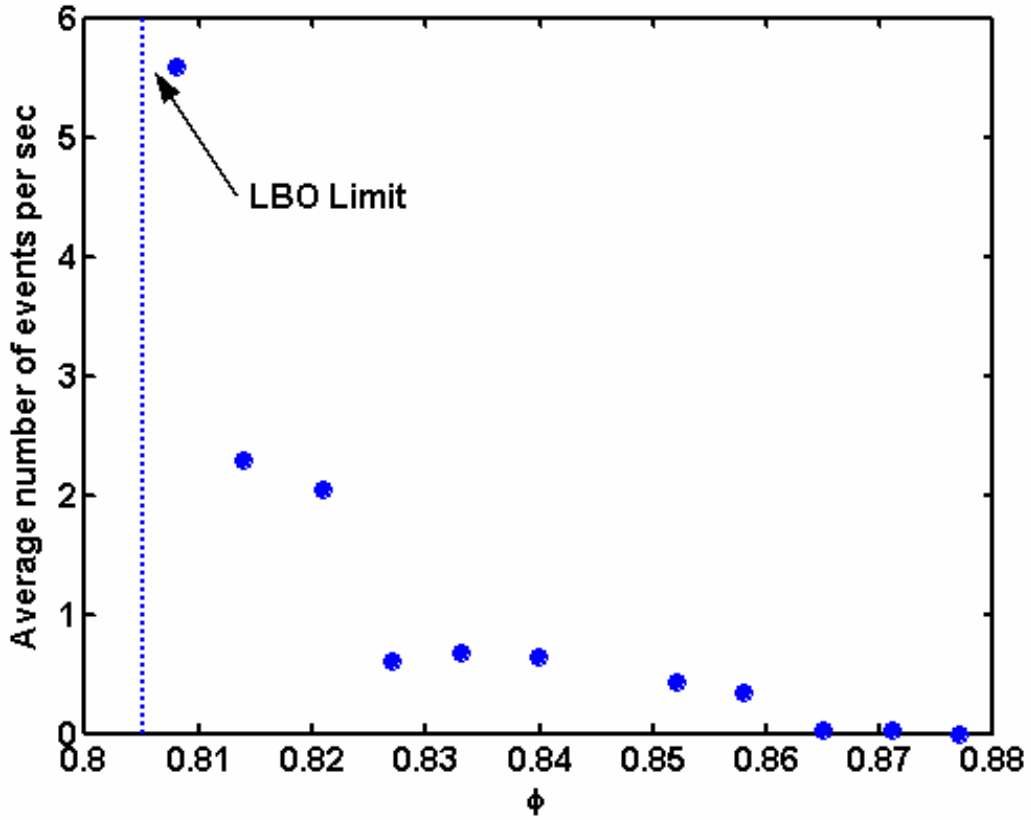
Precursor Identification - Thresholding



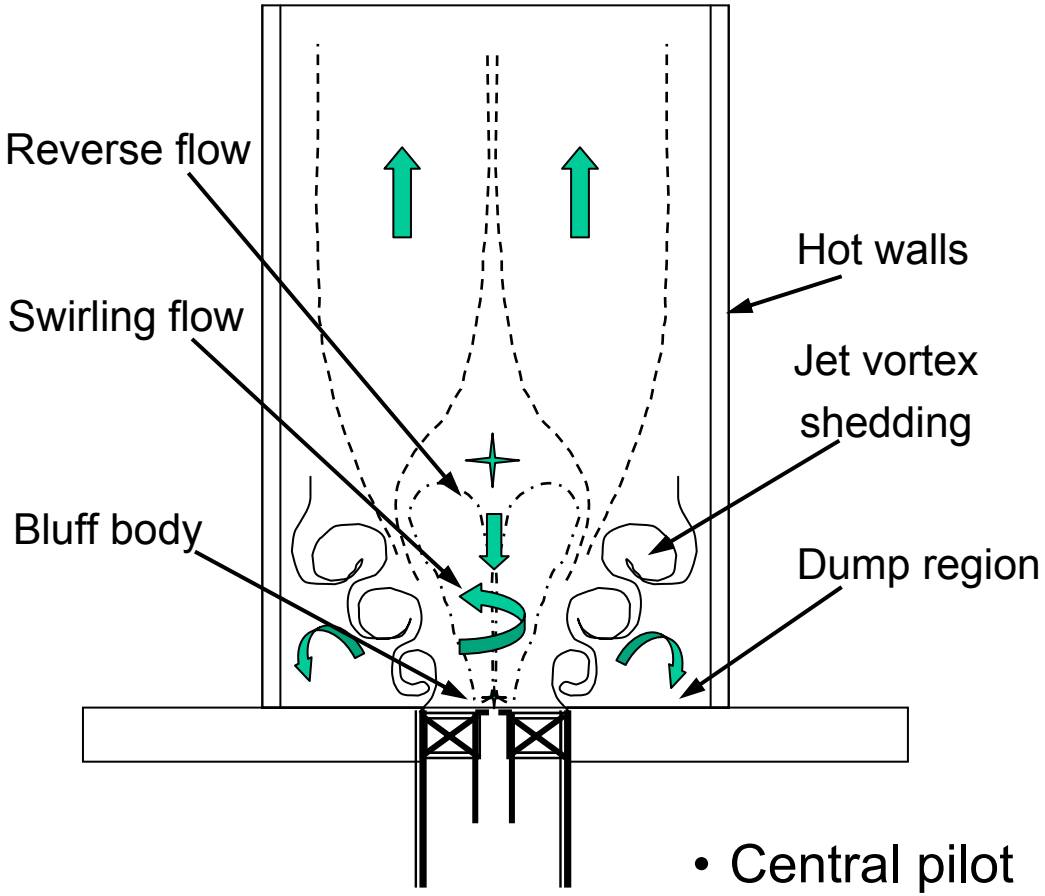
- Identification
  - Fourier/wavelet analysis
  - Statistical methods
  - ✓ Thresholding
- Double threshold
  - Less susceptible to noise

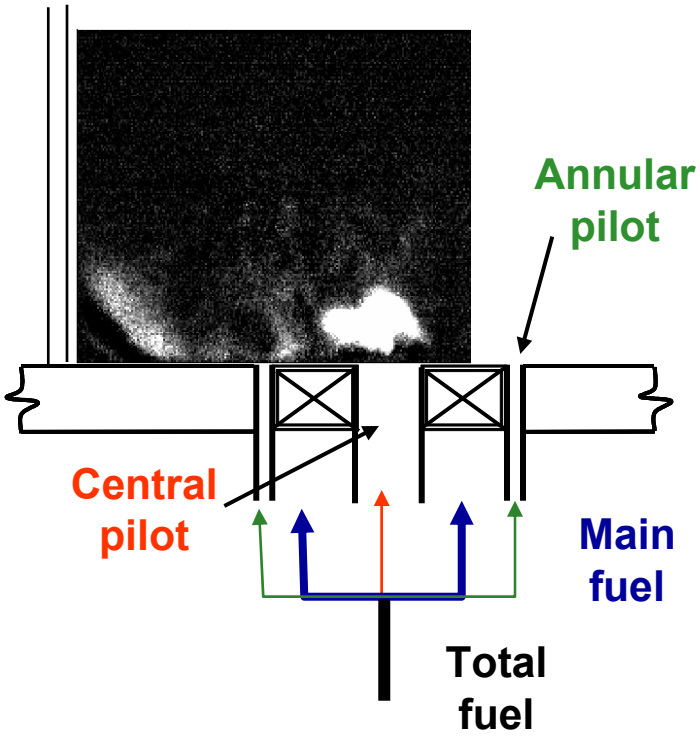
LBO Proximity Parameter

- Number of events
- Time between events
- Duration of single event
- Total duration of events



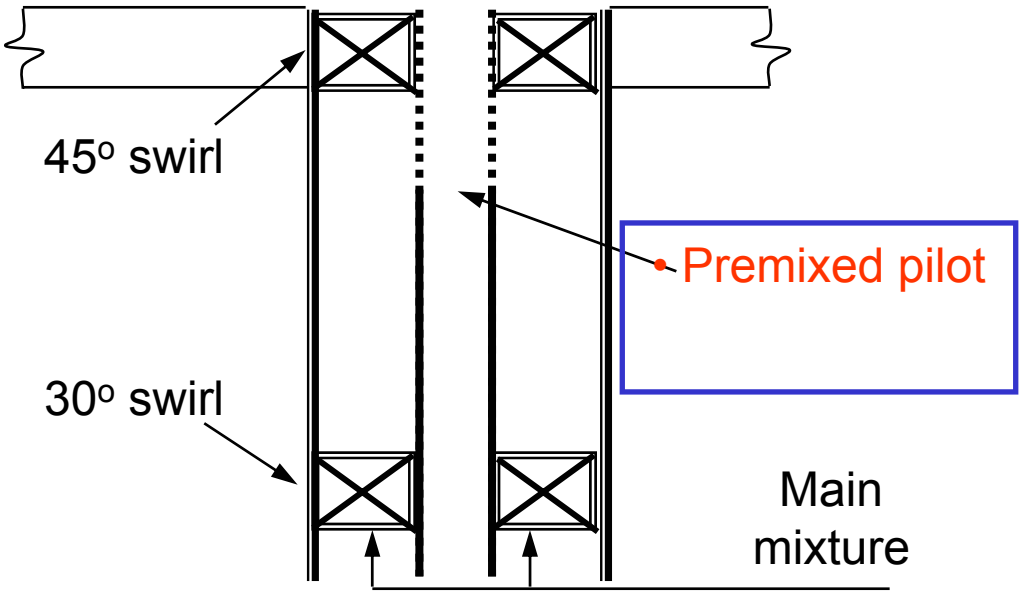
Stabilization and Piloting





- Central pilot
  >10% any effect
- Annular pilot
  >12% any effect

Preinjection Pilot



Third possibility:

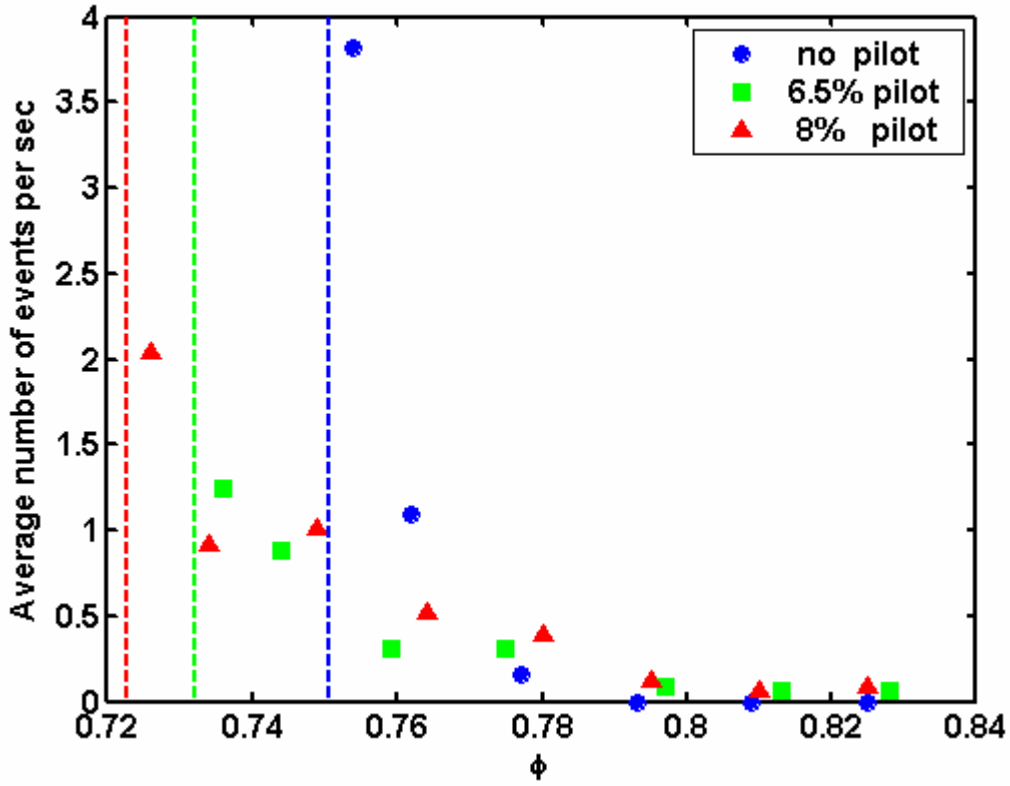
✓ Central premixed pilot

>5% effective

- Air addition improves pilot
  - Earlier mixing with primary?
  - Change in equivalence ratio?
  - Momentum addition in the center?

Results with Piloting

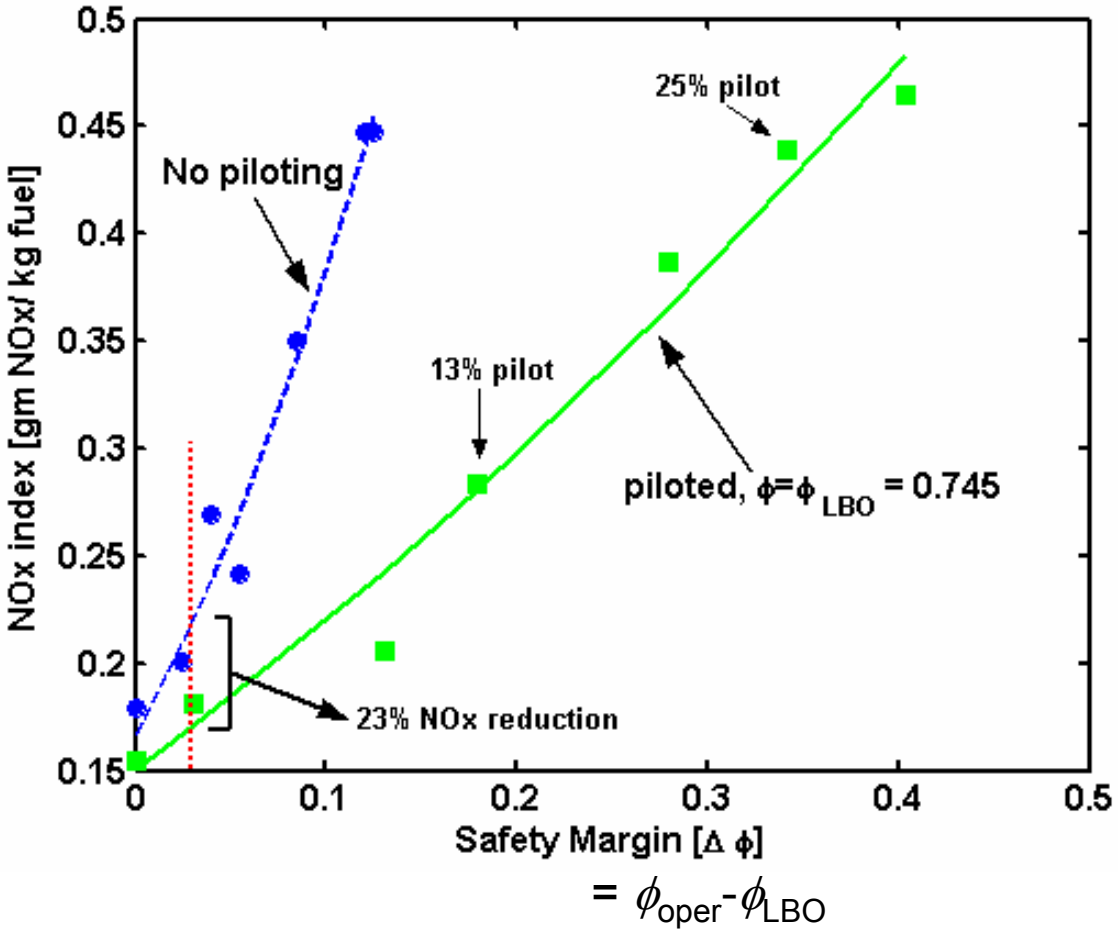
LBO limit moves



- LBO limit moves to leaner ϕ
  - ✓ Increased safety margin
- Sensing of precursors still works

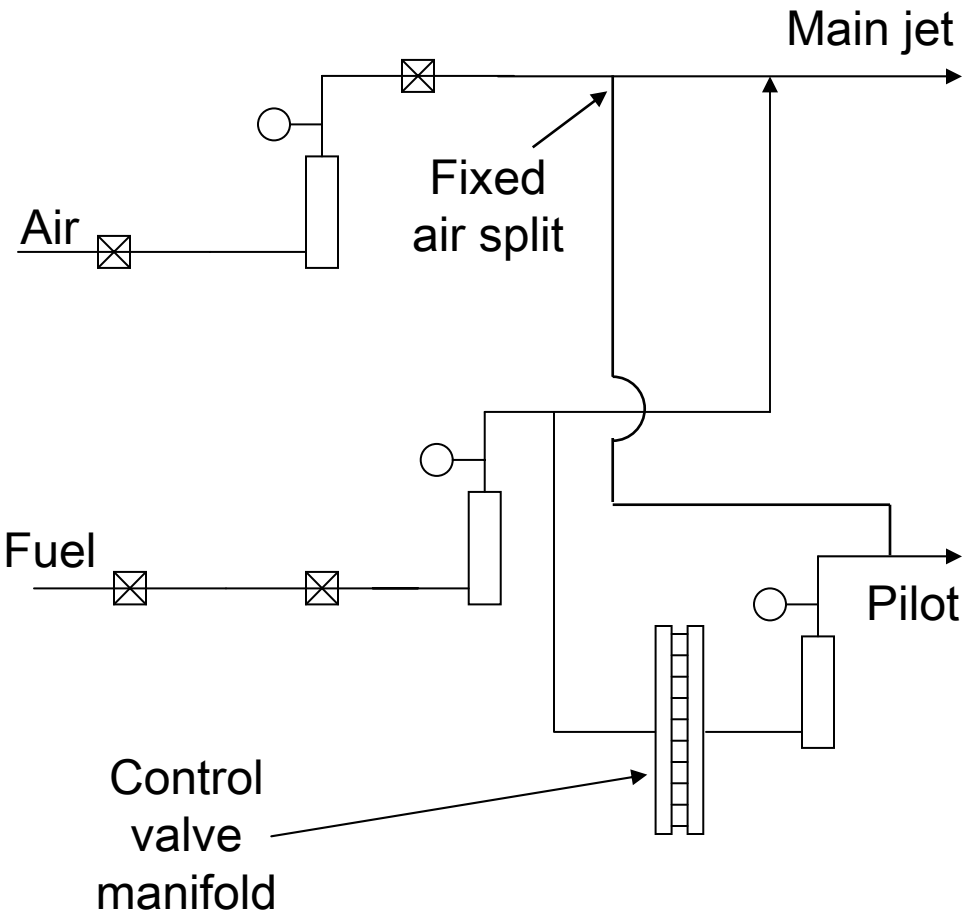
➢ How does piloting affect NOx?

NOx Reduction



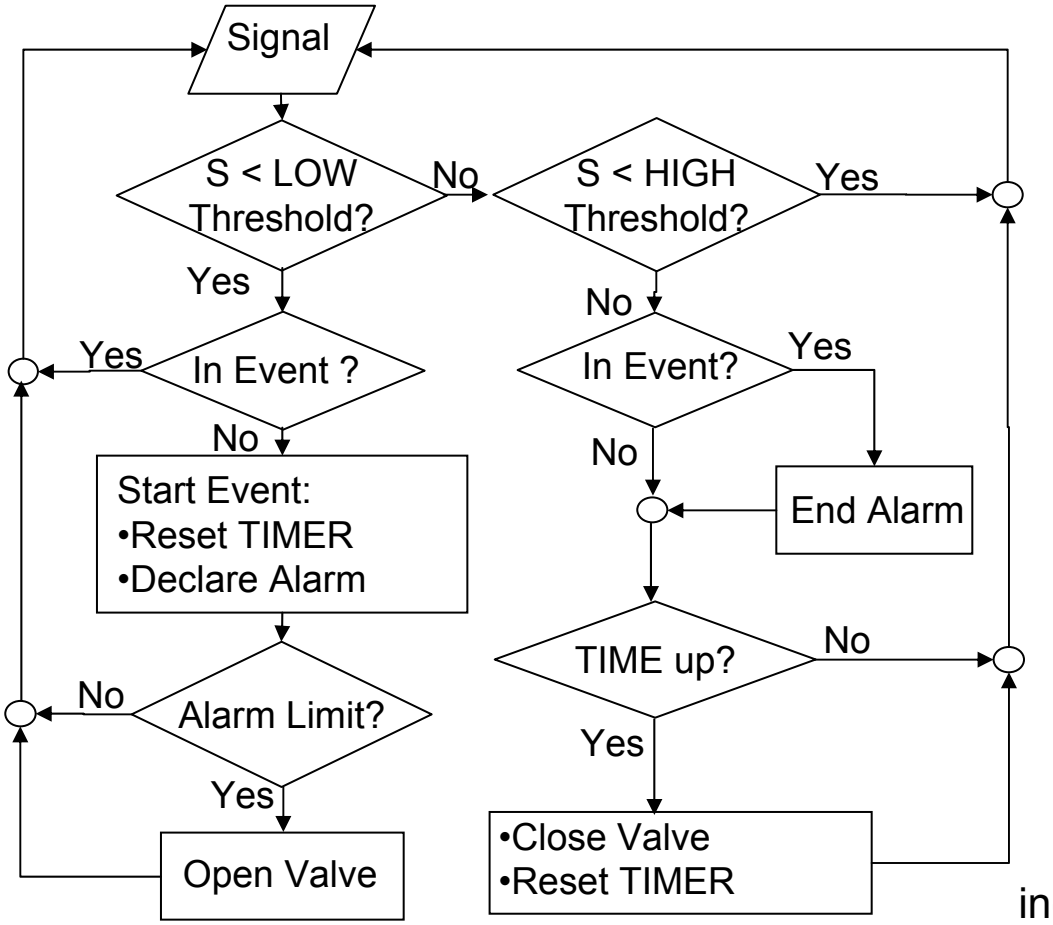
- Higher pilot fraction
  - Increases safety margin
  - Increases NOx
- For same safety margin
  - Piloting decreases NOx
  - At $\Delta\phi$=0.04 (6% pilot) 25% NOx reduction

Digital Flow Control System

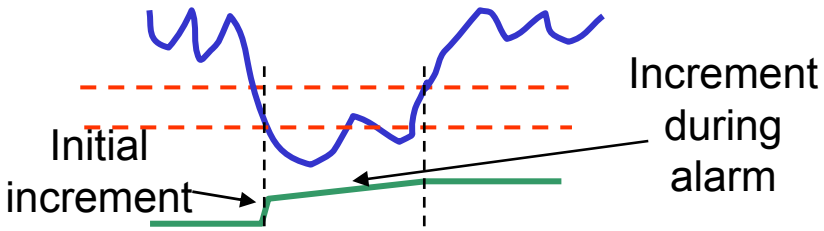


- Constant power control
  - Only control pilot fuel fraction
  - Fixed pilot air fraction
- Actuation
  - Manifold with 10 miniature solenoid valves
  - Pulse width modulation for fine control

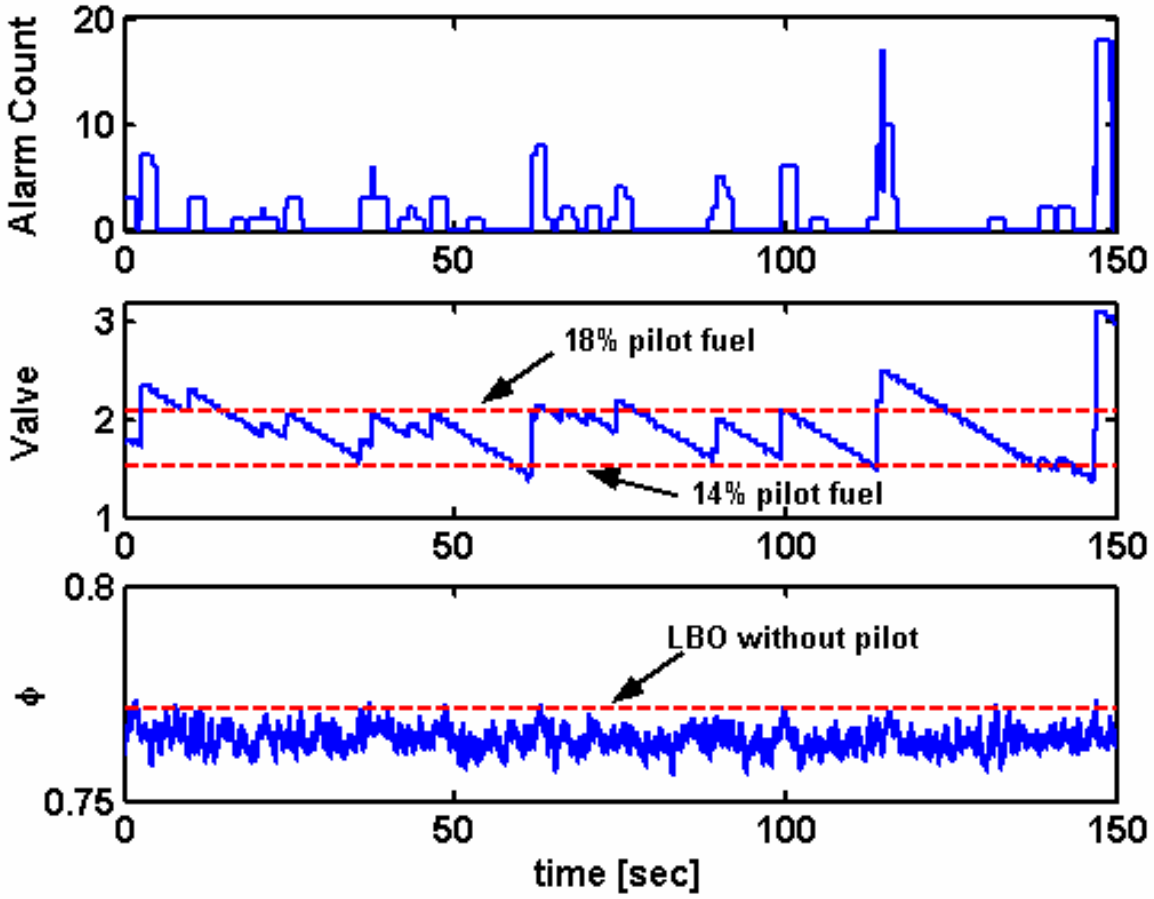
Control Scheme



- Rule Based Control
  - Determine action based on number and duration of precursor events
  - Parameters
    - Threshold values
    - Maximum alarm count
    - Valve opening and closing rates
    - Actuation and flow delays

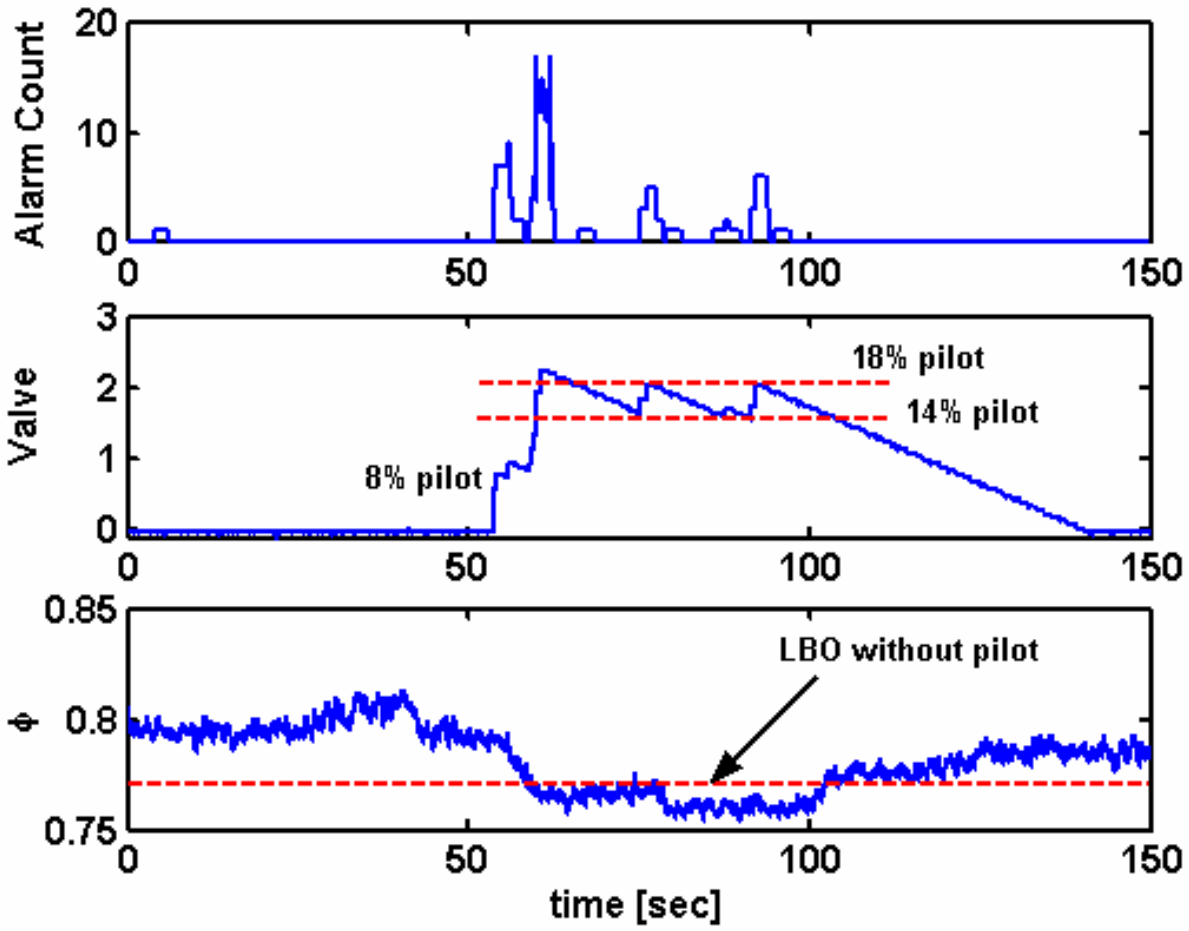


Control Results: Equilibrium



- Parameters
  - Thresholds
    - 35% and 40%
  - Alarm limit = 2/sec
  - Valve actuation
    - At alarm start 1%
    - Increment 0.1% during an alarm
    - Decrement 0.5% when timer expired (0.5 sec cycle)
- Stationary state achieved
- Operation below LBO limit without pilot

Control Results – Air Fluctuations



- Response of control system to operating condition changes
  - –Manual changes in total air flow

✓Control system responds to operating point changes

Summary

- Complete active control system developed to suppress lean blowout
- Sensing
  - OH chemiluminescence detects extinction events
  - Increase in events gives LBO proximity
- Piloting stabilizes flame
  - Fuel redistributed for constant power operation
  - Central premixed pilot
  - Reduces NOx for the same equivalent safety margin
- LBO controller
  - Rule based control
  - Minimizes pilot fuel fraction to minimize NOx
  - Successfully adapts to changes in operating conditions

Further Work

- Extend approach
  - Higher pressures
  - Liquid-fuel
  - Nonpremixed
- Sensing
  - Locations, optical access
  - Acoustic pressure sensing
- Actuation
  - Adapt piloting approach to other combustors
  - Requires further study of pilot mixing and stabilization
- Controller
  - Develop method to optimize control parameters
  - Improve time response (e.g., gradient based)