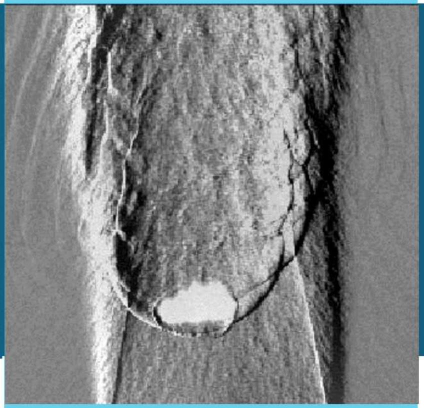
SAND2019-6327C

Interrogation of Burst-Mode Laser-Induced Plasma in Overexpanded Jets at 300-500 kHz Repetition-Rate via Advanced Spectroscopic and Imaging Diagnostics



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June 22nd, Gordon Research Seminar

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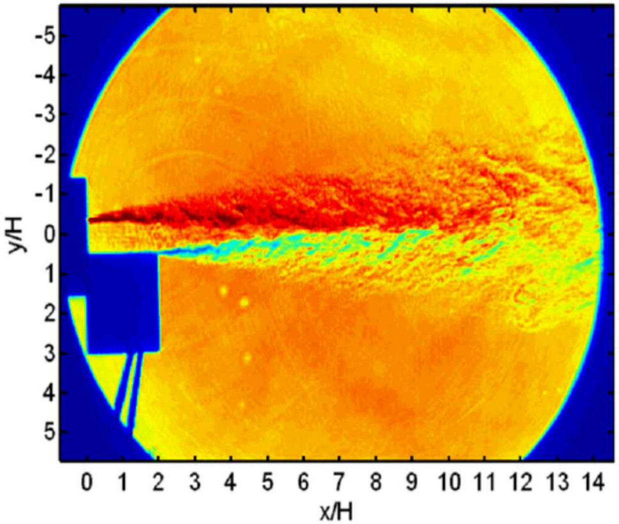
Energy deposition in flows by nanosecond pulse discharges

- Arc filaments
  - High temperature, constricted plasmas
  - Flow control via heating [Leonov, 2004 & Webb et al., 2013]
  - Rapid localized heating generates strong compression wave; [Samimy et al., 2007 & Adamovich, 2009]

Four DC arc filament discharges interacting with a jet



[Adamovich, 2009]

- Relative energy imparted into the flow; [Knight, 2008]

$$\varepsilon = Q / \rho_\infty C_p T_\infty V$$

- Q: laser pulse energy (kJ)
- ρ_∞: jet exit density (kg/m^3)
- C_p: heat capacity (kJ/kg/K)
- T_∞: jet exit temperature (K)
- V: plasma volume (m^3)

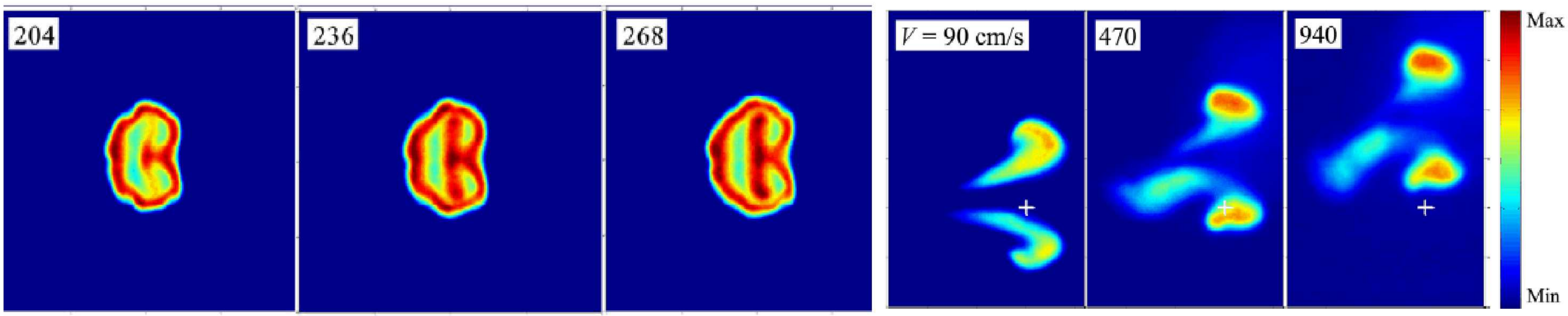
- Previous work have studied laser induced plasmas with ε = 77-2100; [Adelgren et al., 2005]

- Nanosecond pulsed plasma actuators:
  - Must be located at walls or jet exits
  - High repetition rates: $\tau \leq 100$ kHz
  - Strong scaling implications for large volume flows

Thermal effects of laser-induced plasmas

- Provides non-intrusive deposition with high energy density
- Rapid implementation allows changes in location, energy, and repetition rate
- **Flow interaction time limited by the repetition rate of the laser**

Mean OH-PLIF images of laser-induced ignition kernel



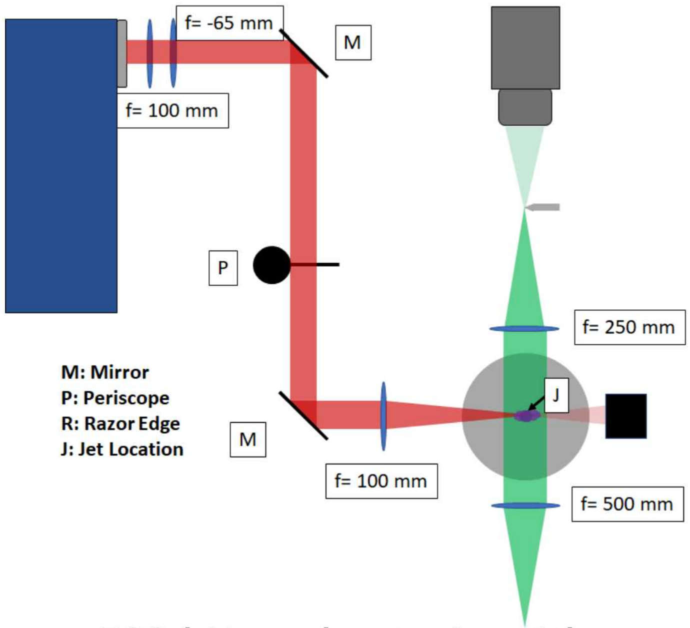
[Mulla et al., 2016]

- Flame kernel size increases with deposited laser energy → stronger shockwaves [Mulla et al., 2016]
- Ignition enhancement from laser-induced plasmas in high energy flows is dependent on plasma surface area [Wermer et al., 2017]

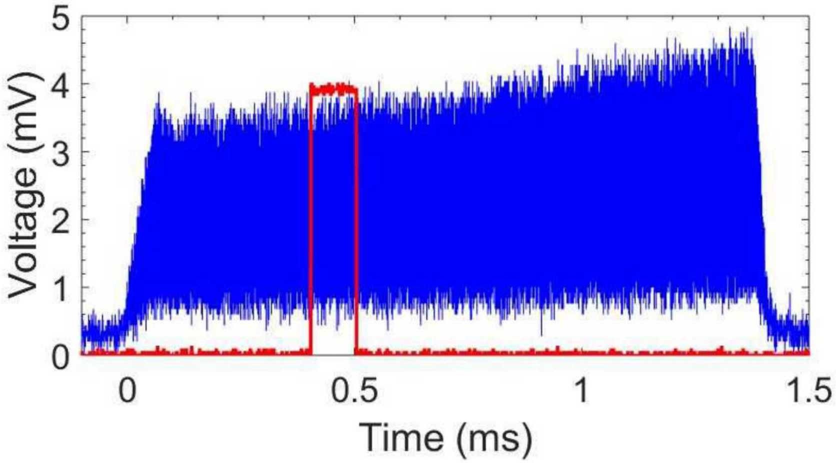
Explore high-bandwidth effects of supersonic flows on pulse-burst laser-induced plasmas

Determine the conditions to sustain a pulse-burst laser-induced plasma at high Re jets

Experimental design



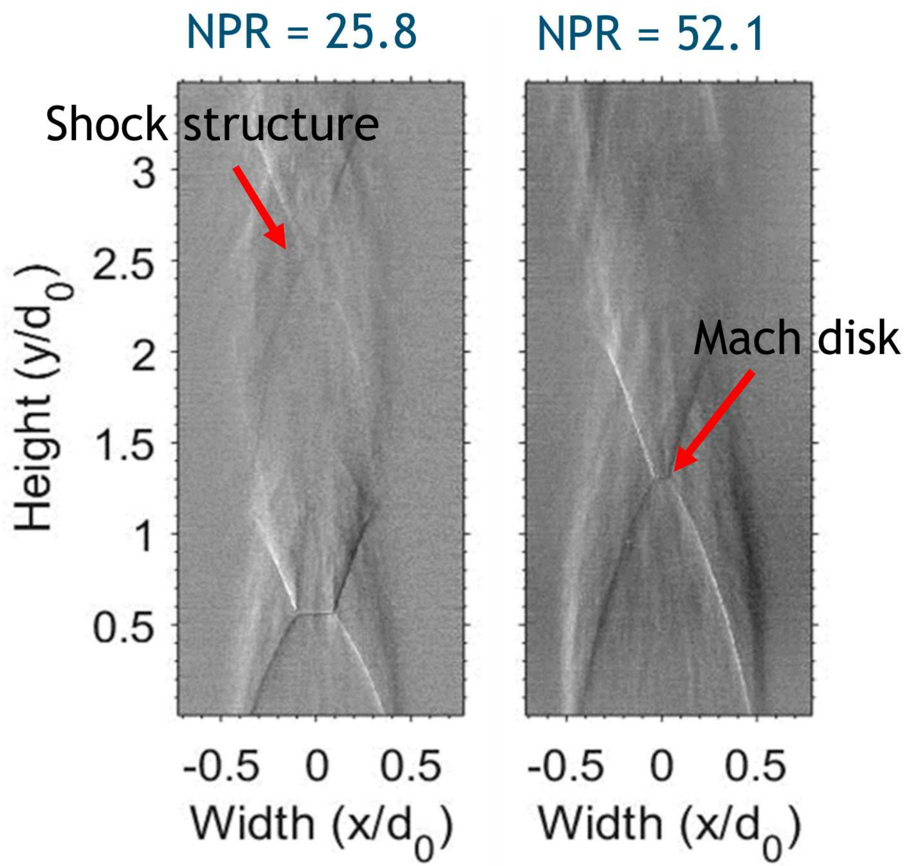
500 kHz pulse train with camera gate



Burst rate: 5- 500 kHz, Burst duration: 1.5-10.5 ms

Total burst energy E ~ 15 J, $\varepsilon \sim 13 - 300$

Imaging of overexpanded, unperturbed jet

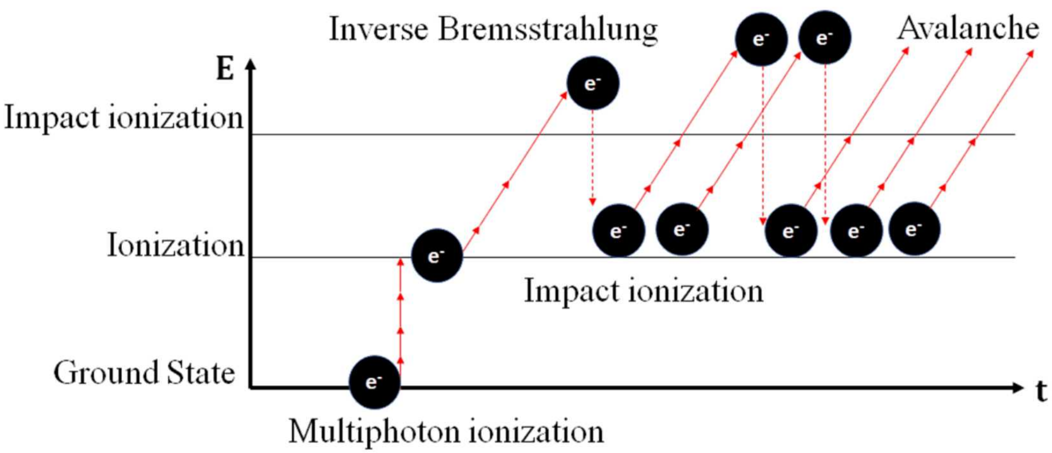


C-D nozzle, M= 3.71

Nozzle pressure ratio (NPR) ~19.5-52.1

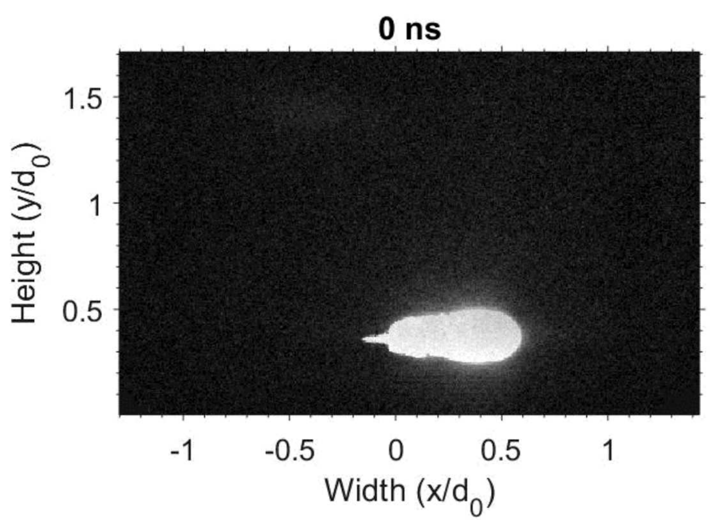
T_{exit} = 80 K, v_{exit} = 660 m/s $d_0 = 6\ mm$

Laser-induced plasmas in quiescent air



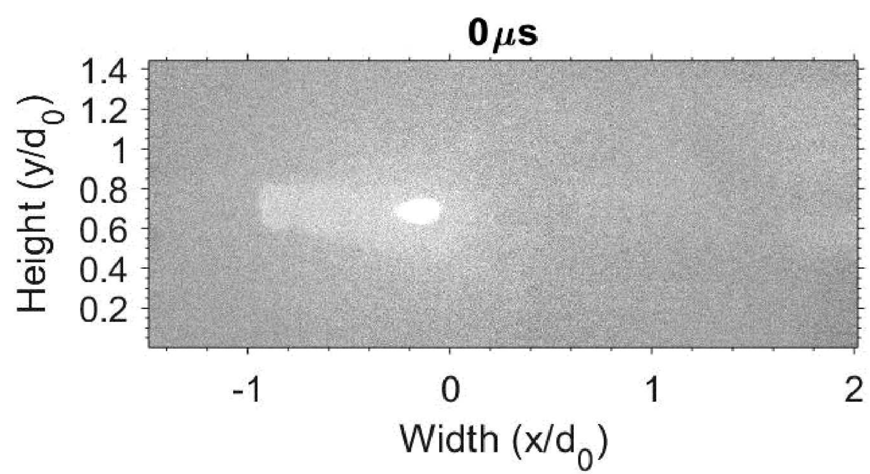
- Formation by two ionization mechanisms
  - Multiphoton → seed electron generation
  - Collisional cascade → electron avalanche
- Vortex formation generates high velocity, hot air jet
- Breakdown in air is stochastic

Plasma-induced blast wave



E= 310 mJ/pulse; Frame rate = 5 MHz, τ_{exp} = 10 ns

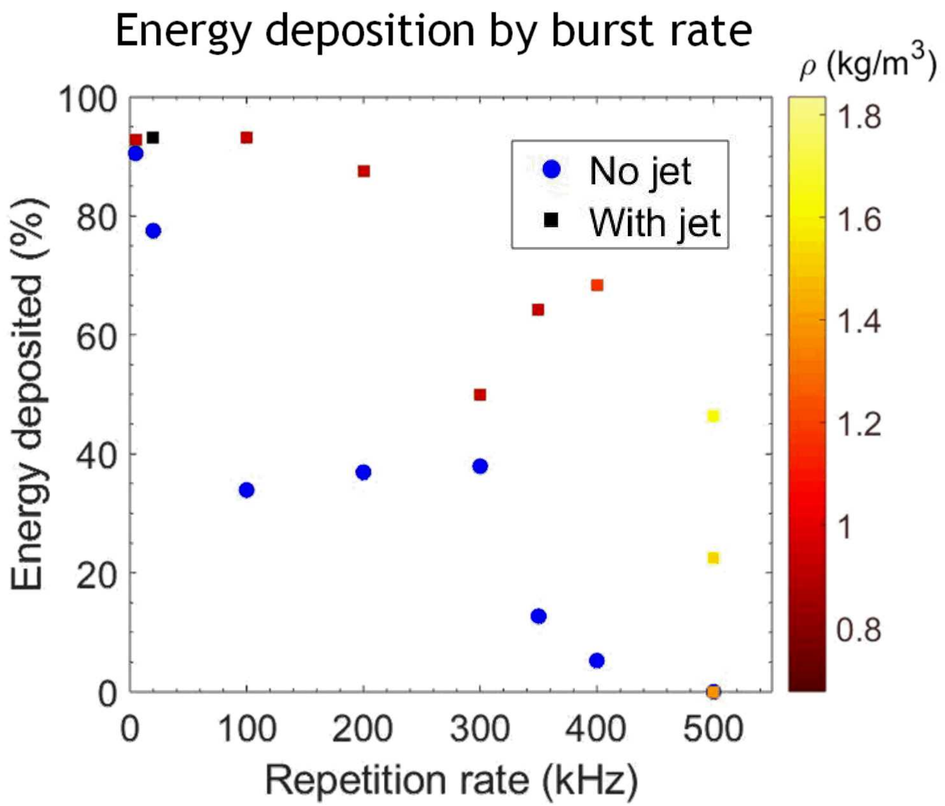
Core gas dynamics



20 kHz burst rate

Frame rate = 60 kHz, τ_{exp} = 1 μs

High repetition-rate breakdown in supersonic flow

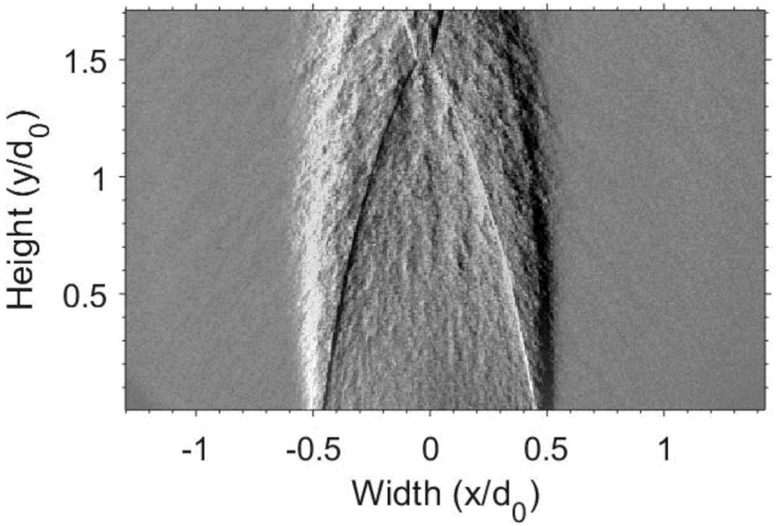


- Stochasticity in pulse-burst laser-induced plasma in quiescent air increases at higher burst rates
- Refresh rate of the supersonic jet sustains breakdown at τ < 350 kHz
- Sustained breakdown at τ > 350 kHz, requires both greater flow and jet exit density

Coupling pulse-burst laser-induced plasma to the supersonic jet reduces stochasticity

High-bandwidth laser-plasma/jet-flow interactions

Unperturbed jet, NPR = 52.1

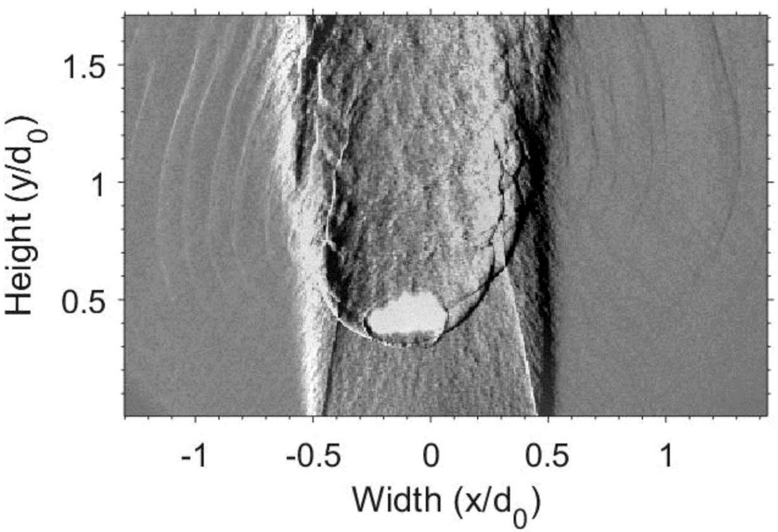


500 kHz burst rate

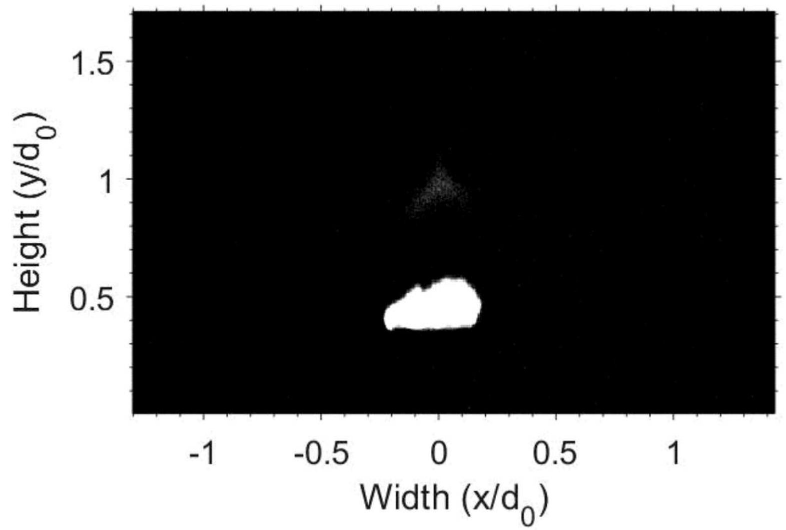
Frame rate 5 MHz, exposure 10 ns

- High repetition breakdown in the flow
- Permanent jet modulation
- Continuous plasma emission at the jet core
- Shock re-excitation of plasma species

Permanently disrupted jet

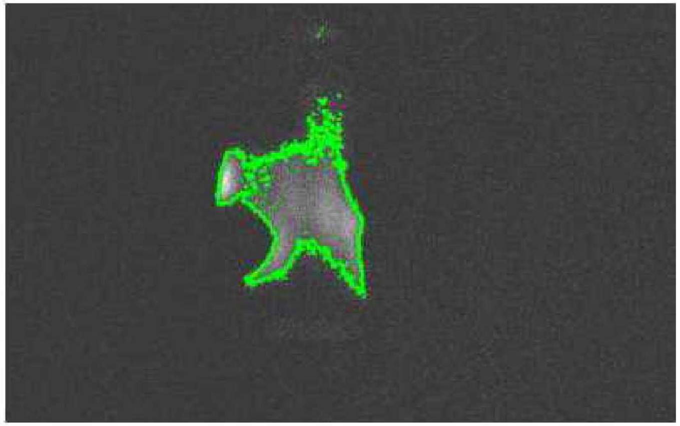


N(II) emission in jet core

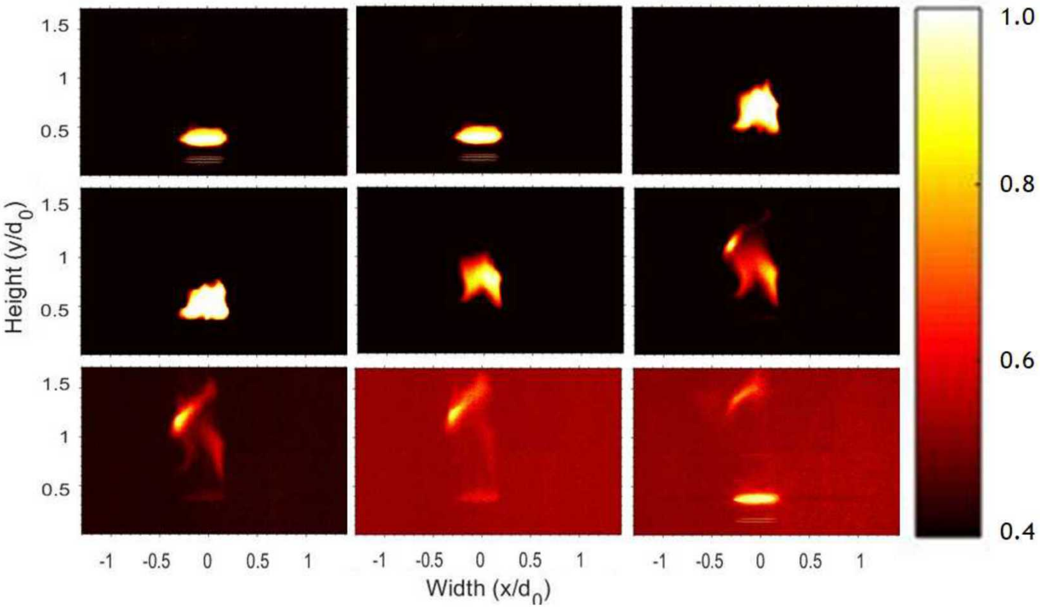


Flow dynamics of the plasma in the jet core

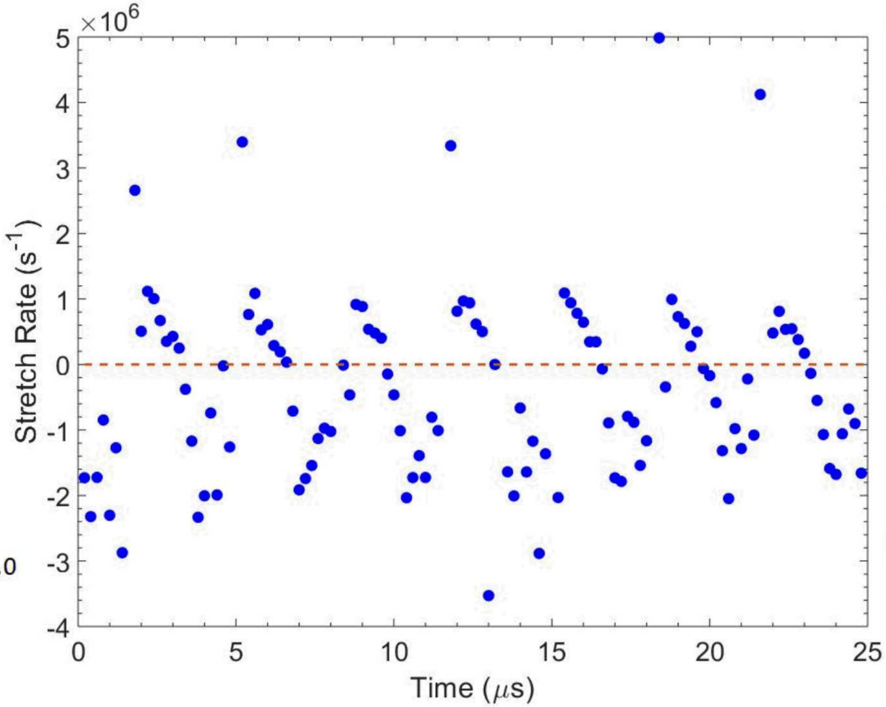
N(II) perimeter and area



Probability of convection path



Plasma stretch rate



Frame rate 5 MHz, exposure 100 ns

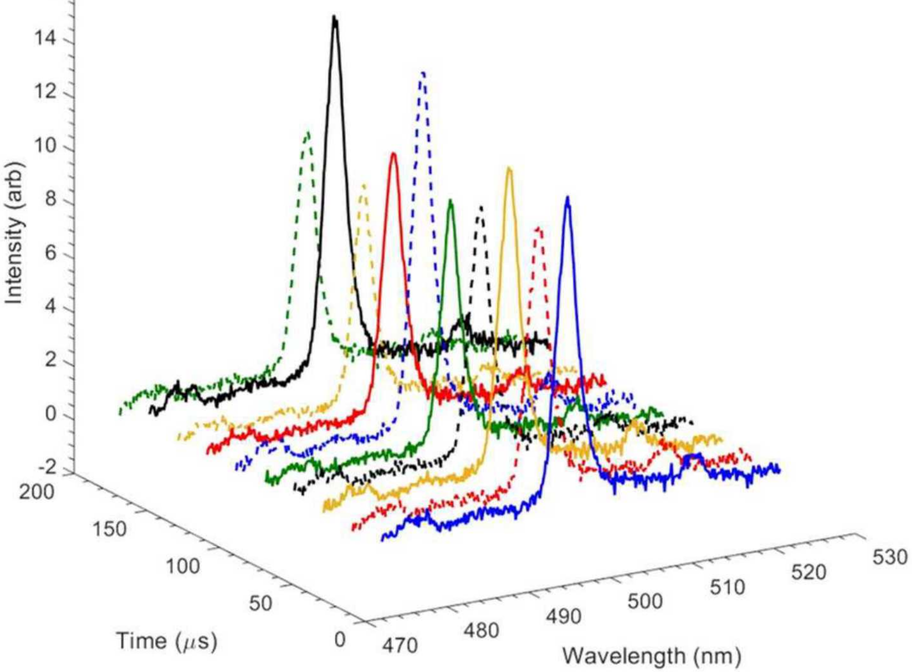
300 kHz burst rate

- Plasma is stretched during convection
- Path of convection is repeatable
- Plasma kernel interaction length

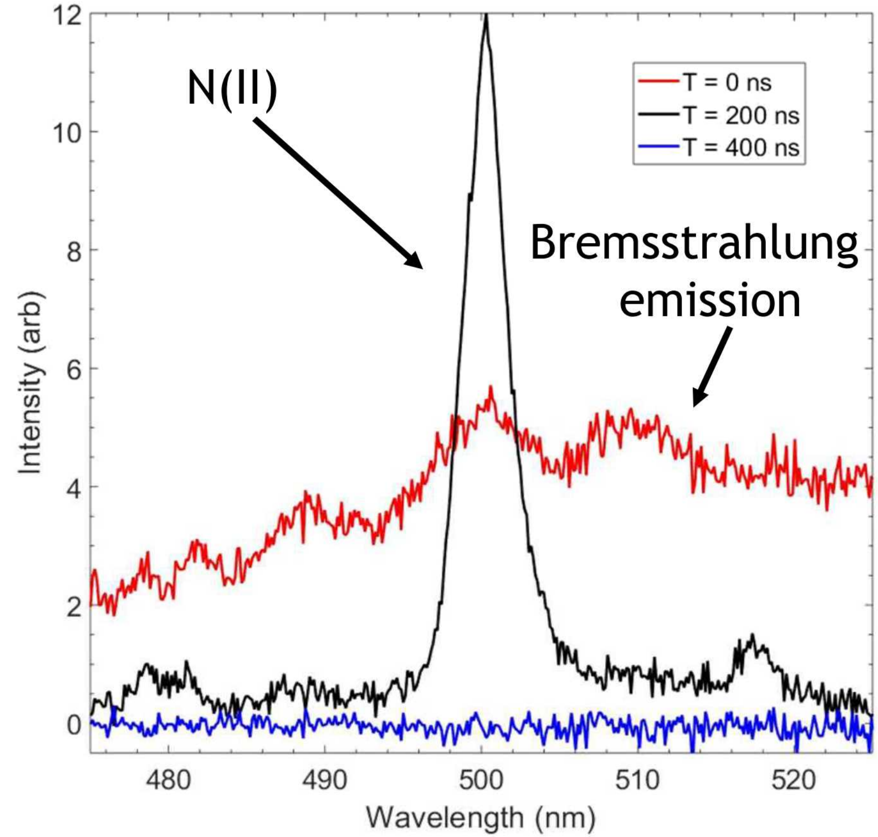
Ultrafast laser-induced breakdown spectroscopy (LIBS)

Variance throughout the burst

$\sigma^2 = 3.8507$



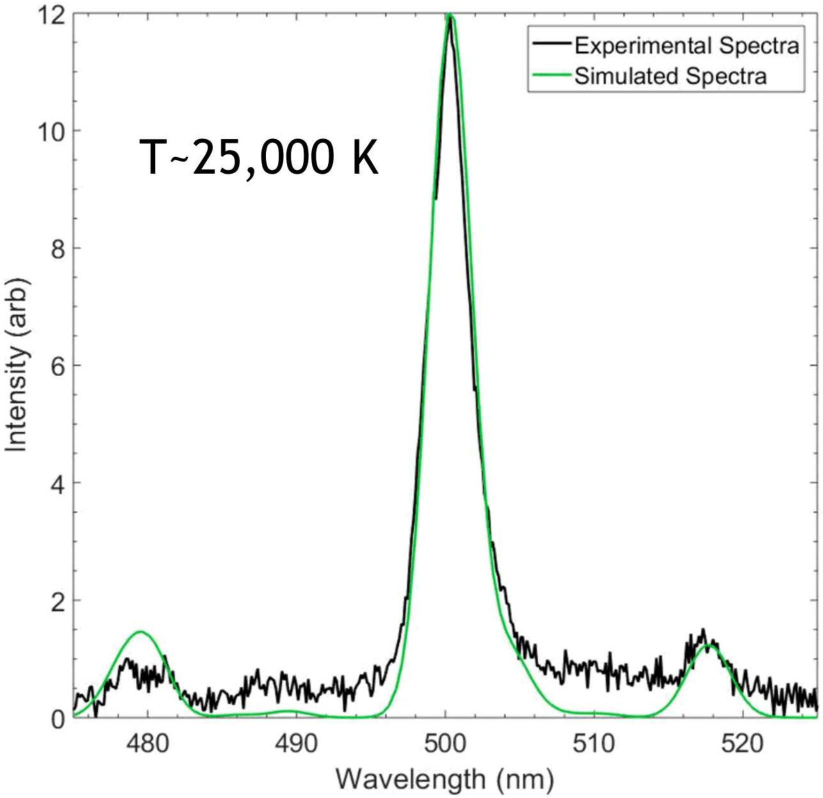
Time evolution of single LIP



- Plasma varies shot-to-shot throughout burst
- Plasma initially has broadband emission from electron recombination processes
- Strong spectral features appear as plasma is decaying
- By 400 ns after breakdown, plasma no longer emits

Preliminary temperature measurements

N(II) Emission



E= 17 mJ/pulse; Burst rate= 500 kHz;

Frame rate = 5 MHz, τ_{exp} = 100 ns

- Spectra was fit using NIST LIBS database
- Chip dispersion ≈ 0.1357 nm/pixel
  - Signal-to-noise tradeoff with resolution
- N_e~ 1e18 cm^{-3}, assumed from previous work
- Peak emission (λ~500 nm) → ^{3}S, ^{5}P, ^{3}D states
  - E_u ~187,000 to 226,000 cm^{-1}
- Secondary emission (λ~518 nm) → ^{5}P°, ^{5}D° states
  - E_u~244,000 cm^{-1}
- Sources of uncertainty
  - Only ionized nitrogen present in spectra
  - Raised baseline in fit

Temperature measurements can be inferred from ultra-high speed single-shot spectra

Conclusions

- At all repetition rates, the presence of the jet was found to be critical and beneficial to repeatable plasma breakdown.

- Substantial deflection of supersonic, oblique shock waves was achieved with a laser focus prior to the jet, within the jet and on the far side of the jet.

- N(II) emission imaging at 5 MHz demonstrated a 500 kHz burst could generate a near continuous plasma held in the core flow.

- High burst rate laser-induced plasmas cause permanent, controllable actuation of the flow for the entire burst period, and this actuation has significant implications for non-intrusive, plasma flame holding

- Ultrafast laser-induced breakdown spectroscopy can be used to make temperature measurements of all laser plasma events

Acknowledgements

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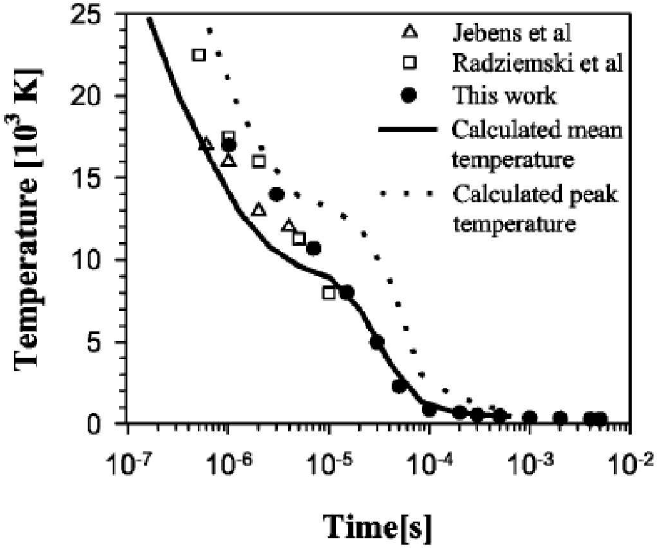
- **Steven Beresh**
- **Marley Kunzler**
- **Seth Spitzer**
- **Ed DeMauro**

Add reference showing plasma temperature versus time



Sobral et al 2000

Previous studies:

16 mJ → 5 kJ/cm^3

Chen et al 2000

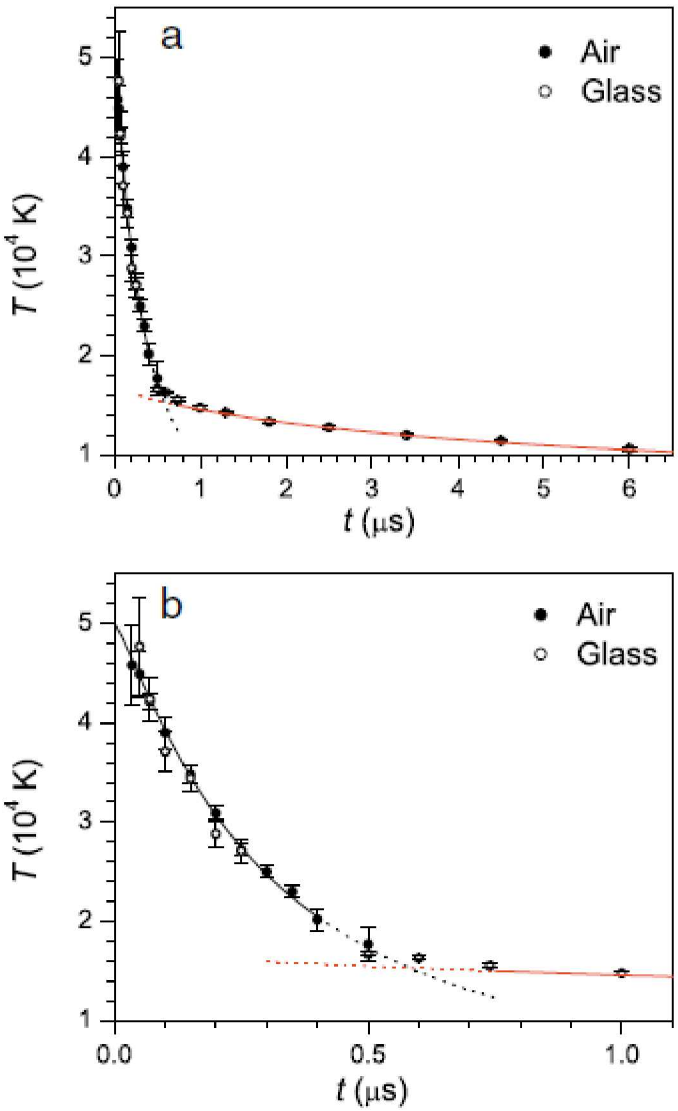
Previous studies:

Ionization energy of N

14.5 eV→ exists between

20,000 – 50,000 K

Below 20,000 N(II) disappears



Aguilera and Aragon, 2014