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On the Use of Multiple Laser Pulses for Improved Plasma Parameters in Filaments

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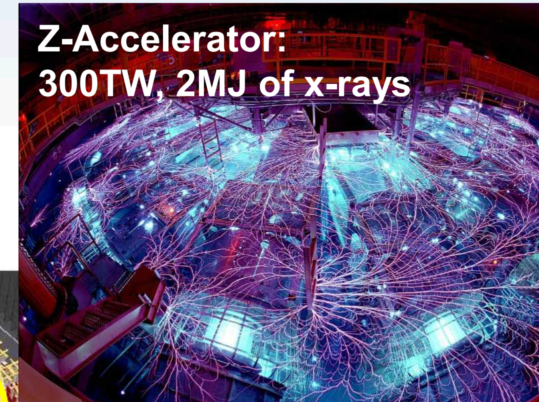
Facility Overview



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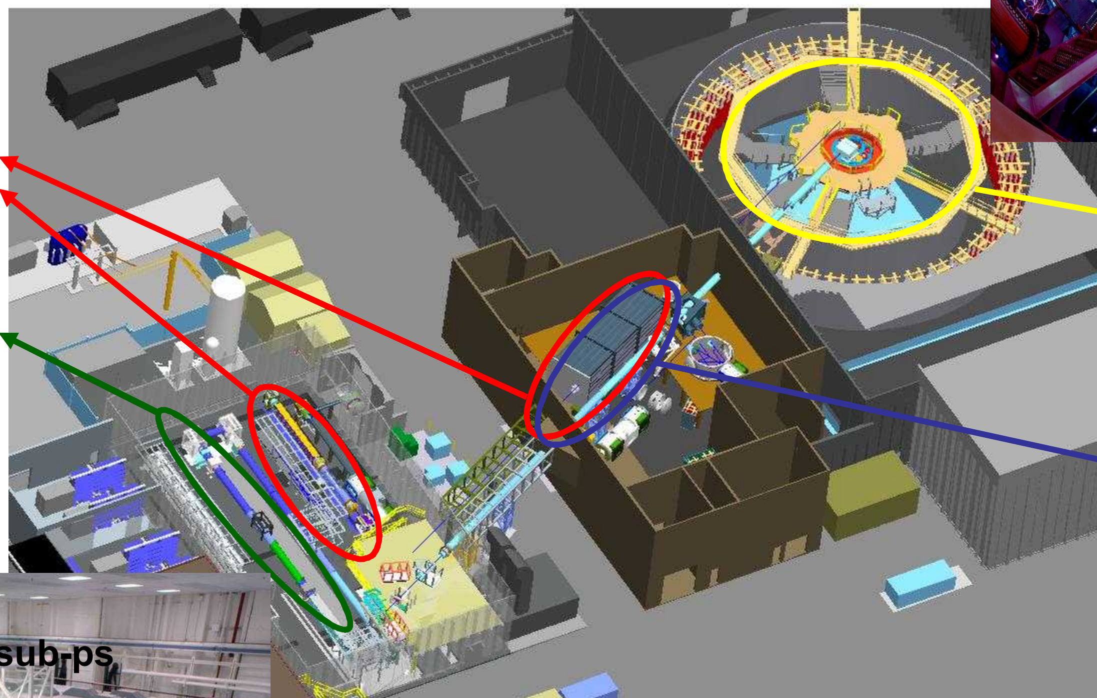

HALO

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- Lasers can be joined with pulsed power for the purposes of:

→X-ray radiography
→Combined high energy density physics/ fusion research
→Laser-triggered spark gaps (MV switching)

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Laser-Triggered Switches For Pulsed Power

Laser-Triggered Switches for Pulsed Power

• Allows switching of up to 6MV at kA levels with ~ns temporal jitters

• Presents engineering challenges due to optics placement in an environment with chemical, high voltage, and shock hazards

Example: Rimfire switch used on Z

• Small laser-triggered gap followed by a self-breaking cascade section

→ SF_6 gas is used for large HV hold-off

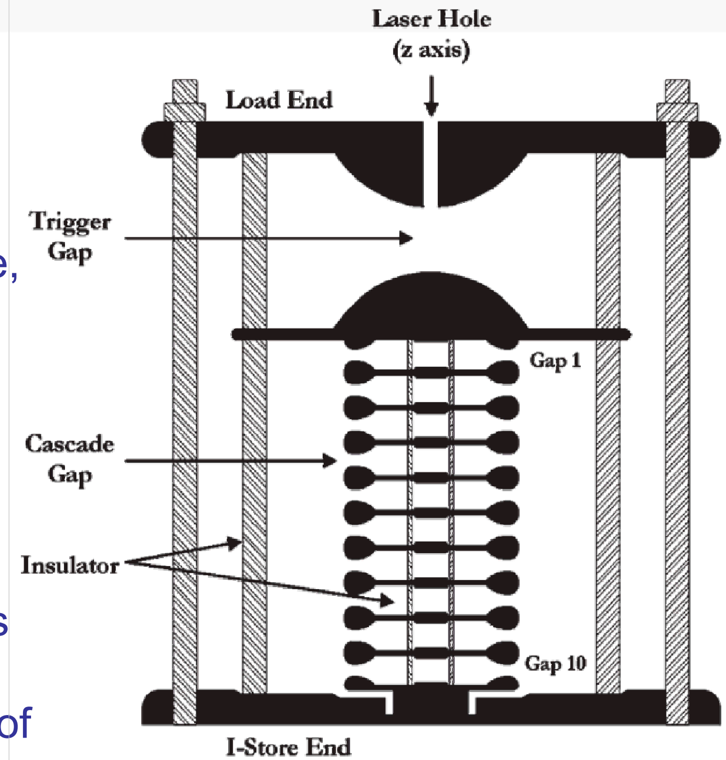
→ UV lasers (<30mJ, ~5ns) efficiently ionize the SF_6 gas in the trigger gap

→ Laser-triggered section can exhibit several hundreds of ps to several ns of jitter

→ Self-break section increases jitter to a few ns

→ Jitter improves if trigger gap increases and the cascade gap decreases or

→ Jitter improves if cascade gap can be triggered in addition (either by single or multiple channels)



From LeChein (IEEE Trans. Plasma Sci., 2006): Trigger gap=4.4cm; Overall gap=44cm

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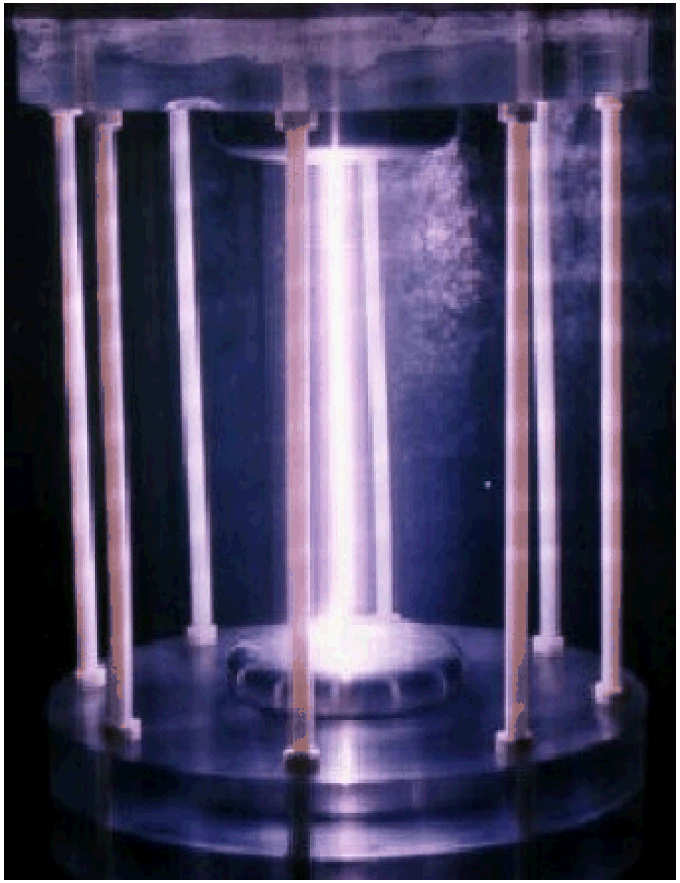
Laser-Triggered Switches: Goals

Applications may include:
- Super-radiant laser sources
- Laser wakefield acceleration
- Directed energy

Generally, these applications need or desire:
- Longer ionized channels
  →Improves switch reliability, jitter, HV
- Lower laser energies
  →Eases laser specs, beam delivery (fiber?)
- Adjustable plasma density
  →Lowers laser energy requirements
- Extended plasma lifetimes
  →Increases gap length/HV; Reduces switch delay
- Reduced temporal jitter
  →Improved pulsed power (pulse shaping, FI, etc.)
- Longer discharge gaps
  →Higher stand-off HV's or less flashovers
- Higher stand-off voltages
  →Improved Pulsed Power systems



From Rambo (J. Opt. A, 2001):
0.30m air gap@0.2MV@0.1J/500fs/248nm

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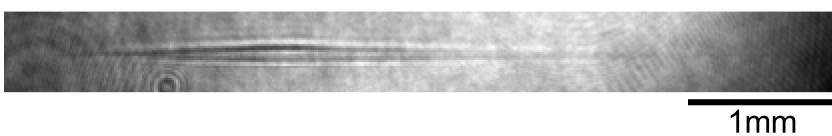
Laser Choices for Switching

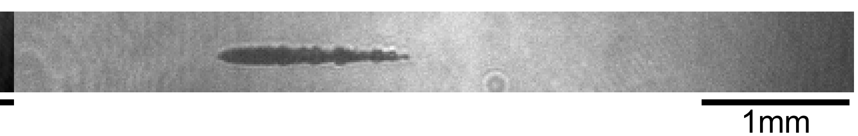
• Long-pulse (ns) lasers
→Cascade gas ionization creates hot plasmas which increases recombination time
→Plasmas in gas are non-uniform due to plasma opacity/discrete beading
→Works well on lower voltage (<300kV) switches with laser ablating electrodes

• UV Long-pulse (ns) and Ultrashort Pulse (USP) lasers
→Multiphoton ionization (MPI) in gas creates "cooler" continuous/uniform plasmas
→Colder plasma recombines faster, which is an issue for longest gaps
→Works well on longer gap high voltage switches by ionizing gas in the gap

• USP, 14mJ, 500fs, 1054nm @ f=25cm



• 8ns, 300mJ, 532nm @ f=25cm



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Plasma Improvement Methodology and Approaches

Plasma control needs and approaches:

• Longer ionized channels

→Focusing with high f/# optics

USP →Filaments

USP →Connected plasma channels (concatenation)

→Axicon focusing

• Lower switch laser energies

USP →Facilitate ionization/ filamentation with high gas pressure in switches

• Adjustable plasma densities

USP →Continuously variable via MPI

• Extended effective plasma lifetimes

USP →Successively delayed USP's to repeatedly ionize the gas

USP →Subsequent ns laser photodetaches electrons weakly bound to ions

USP →Subsequent ns laser inverse bremmstrahlung heats an initial MPI plasma

• Reduced temporal jitters

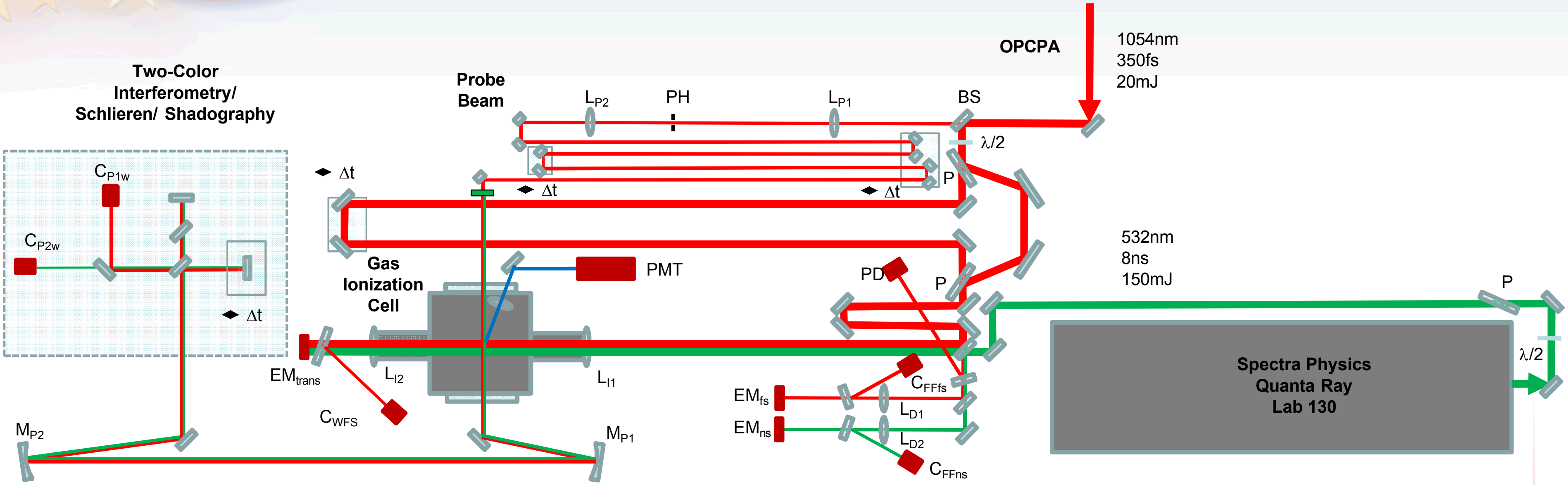
USP →MPI-based USP rapid ionization

USP →Stable USP oscillator clock

USP →USP avoids Pockels cell jitter or laser cavity build up jitter

Premise: Explore approaches via a gas test cell with multiple plasma diagnostics

Experimental Setup



- A sub-ps and ns laser can be combined in various multiple pulse methods for ionization:
  - →Orthogonally polarized USP pulses or USP+ns pulses
  - →Various harmonic options
- A pick-off USP allows 1054nm/527nm optical probing of the plasma
  - →Two-color interferometry allows diagnosis of both electron and neutral particle densities
  - →Schlieren and shadowgraphy can also be used
- Plasma fluorescence imaged onto UV-filtered PMT gives electron density temporal data
- Through-focus energy meter and wavefront sensor can sense laser losses in the plasma generation as well as self-focusing/ plasma defocusing data

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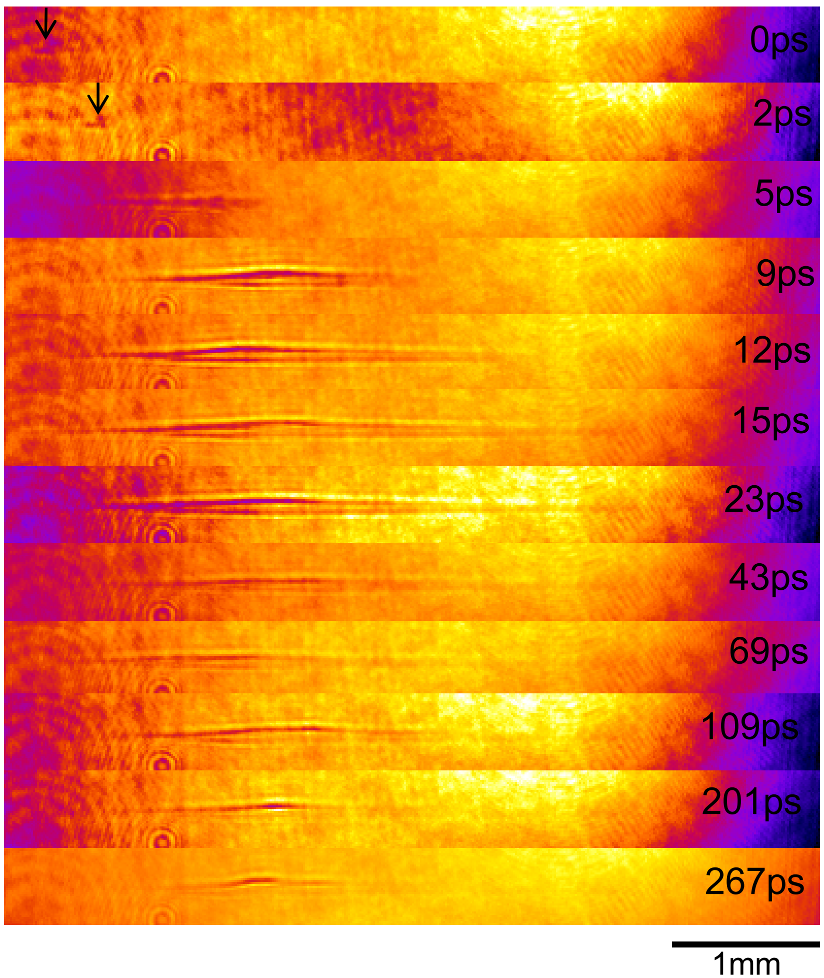
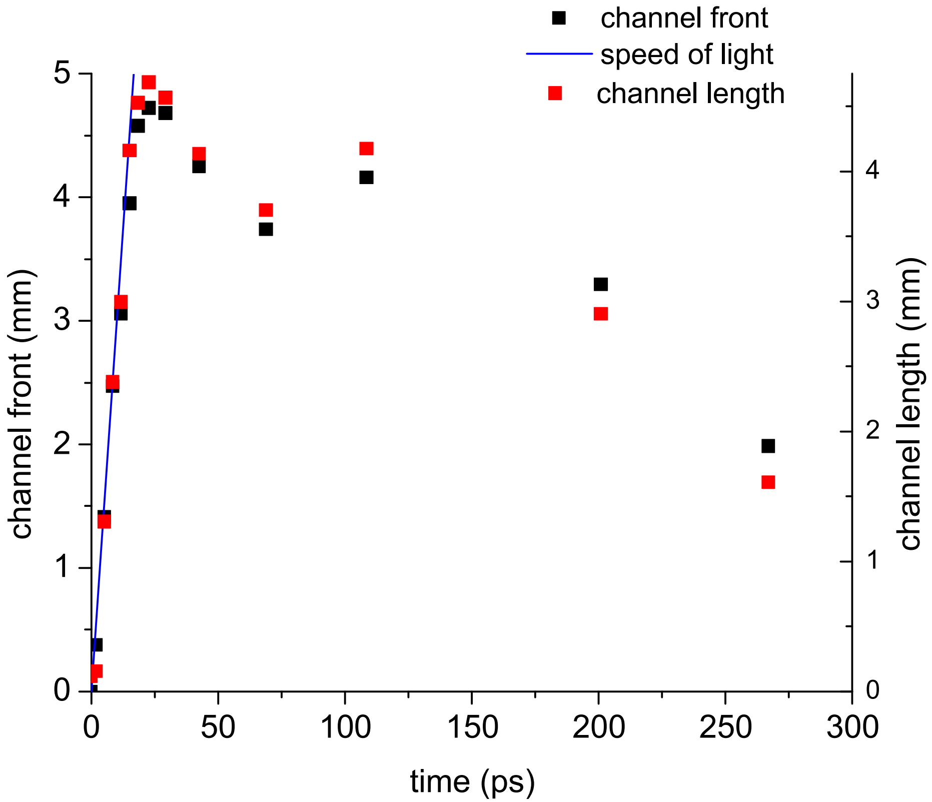
Plasma Diagnostic: Single USP Shadowgraphy

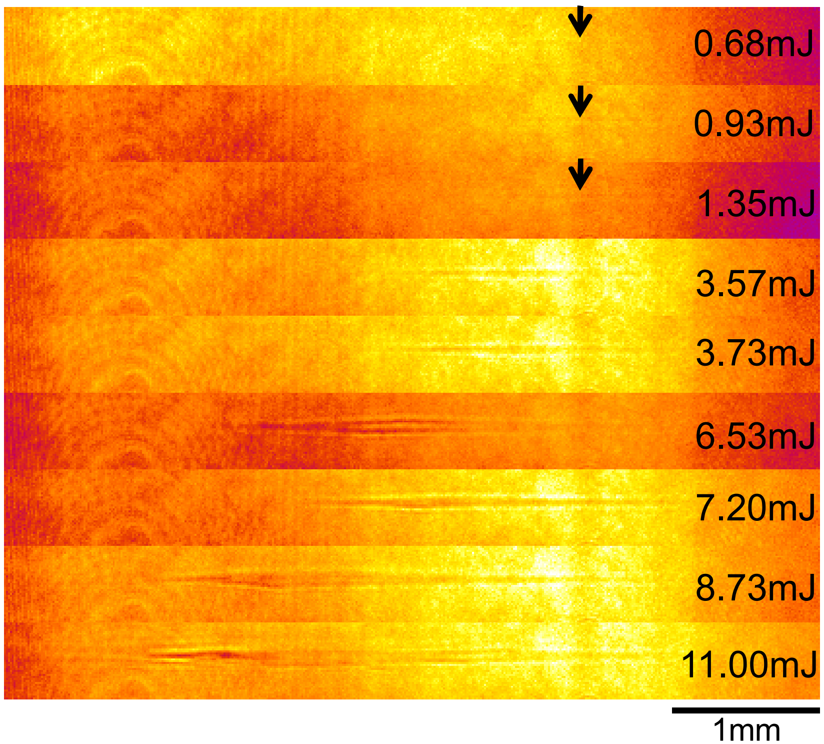


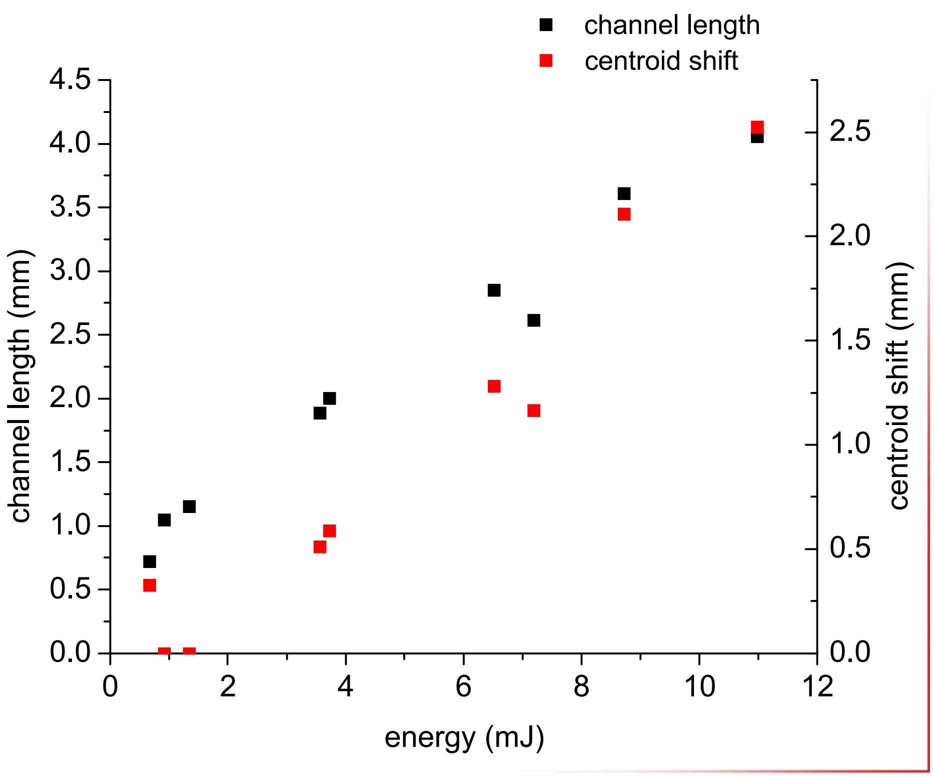
•The ability of the optical probe diagnostics to observe a thin laser-generated plasma transversely is limited to around $10^{18}e^{-}/cm^{3}$.



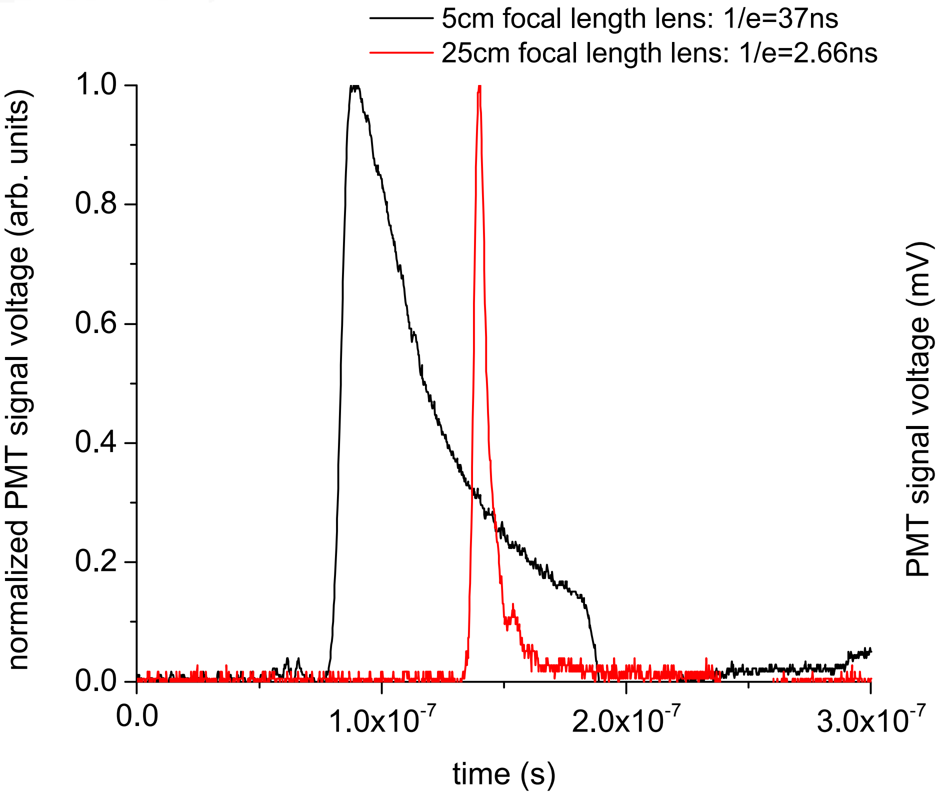
Plasma Diagnostic: Single USP Shadowgraphy

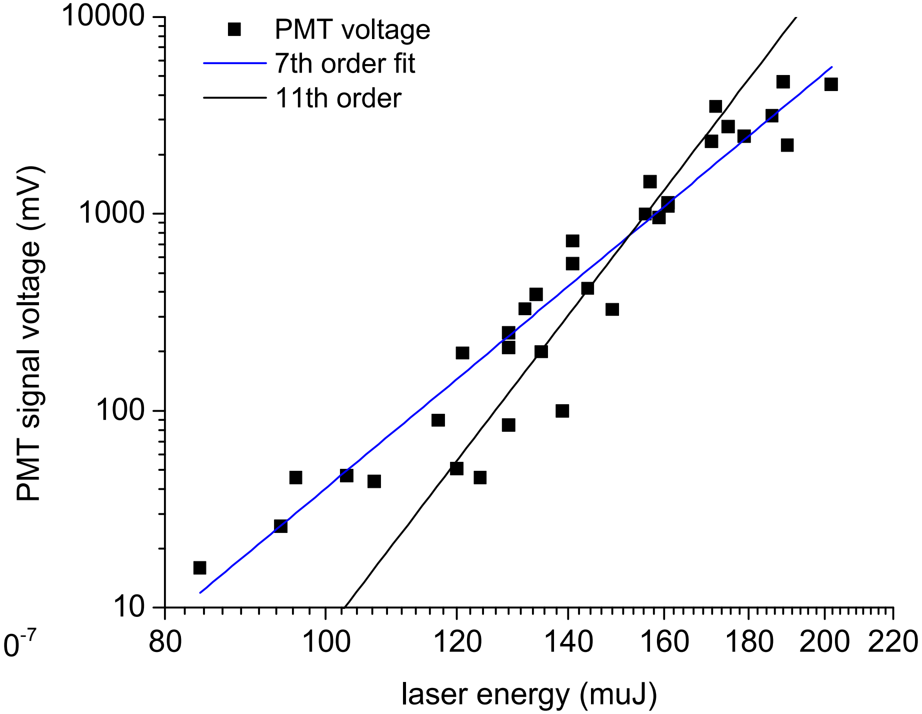
• The increase in energy leads to an extended plasma channel length
• With increasing energy, the centroid shifts to the left due to self-focusing





Plasma Diagnostic: Single USP Plasma Fluorscence





Plasma fluoresence at 391nm from N_2^+ transition scales with electron electron density (*see Theberge et al, Phys.Rev.E (2006)*).

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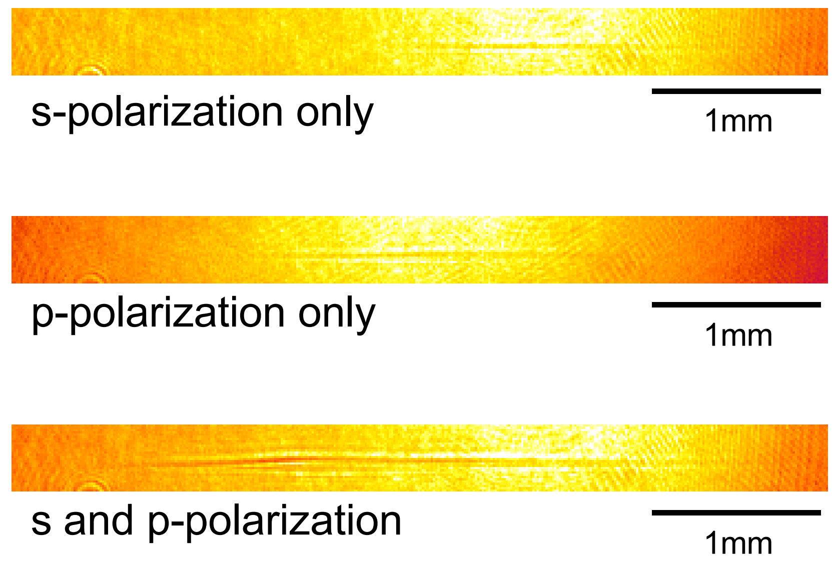
Plasma Improvement Method: "Simultaneous" USP's of Different Energy

- Multiple collinear USP's of different energies can focus at different spatial positions based upon self-focusing and how much a given pulse exceeds the critical power
  → Separated plasmas coalesce into a single longer channel

- We illustrate this with 3mJ of p-polarized USP and 9mJ of s-polarized USP roughly co-temporal and collinear.



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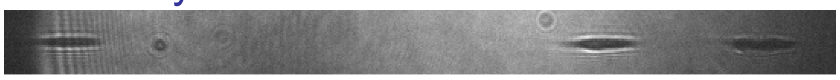
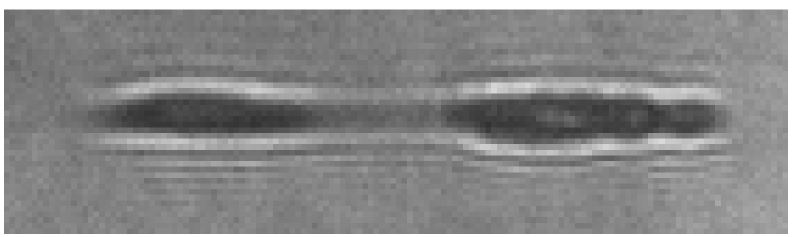
Plasma Improvement Method: "Simultaneous" Multicolor USP

- Chromatic aberration in focusing optics can be used to create spatially separate plasmas which concatenate into longer plasma channel.
- Longer focal lengths and higher harmonic orders both show larger plasma separations which may not coalesce.



1mm

→ Increase in the f/# via input beam diameter reduction can extend these distinct channels to the point where they join



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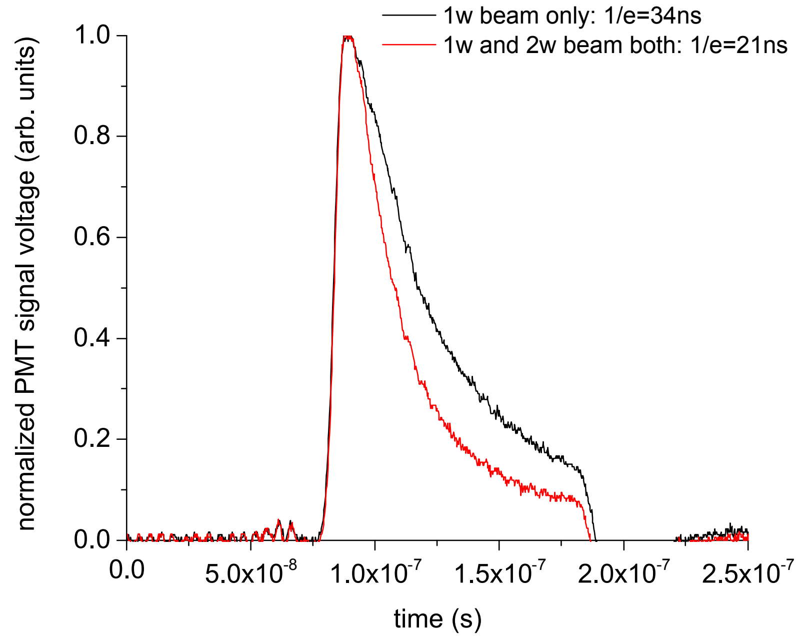
[illegible] ps

1ω, and 2ω USP focused with an f=5cm lens



- For a fixed 1ω initial energy, the plasma channel length is extended for a multi-color USP.
- However, the 1ω only plasma is hotter than the lower energy 1, and 2ω plasma spots and hence has a slightly longer plasma lifetime.

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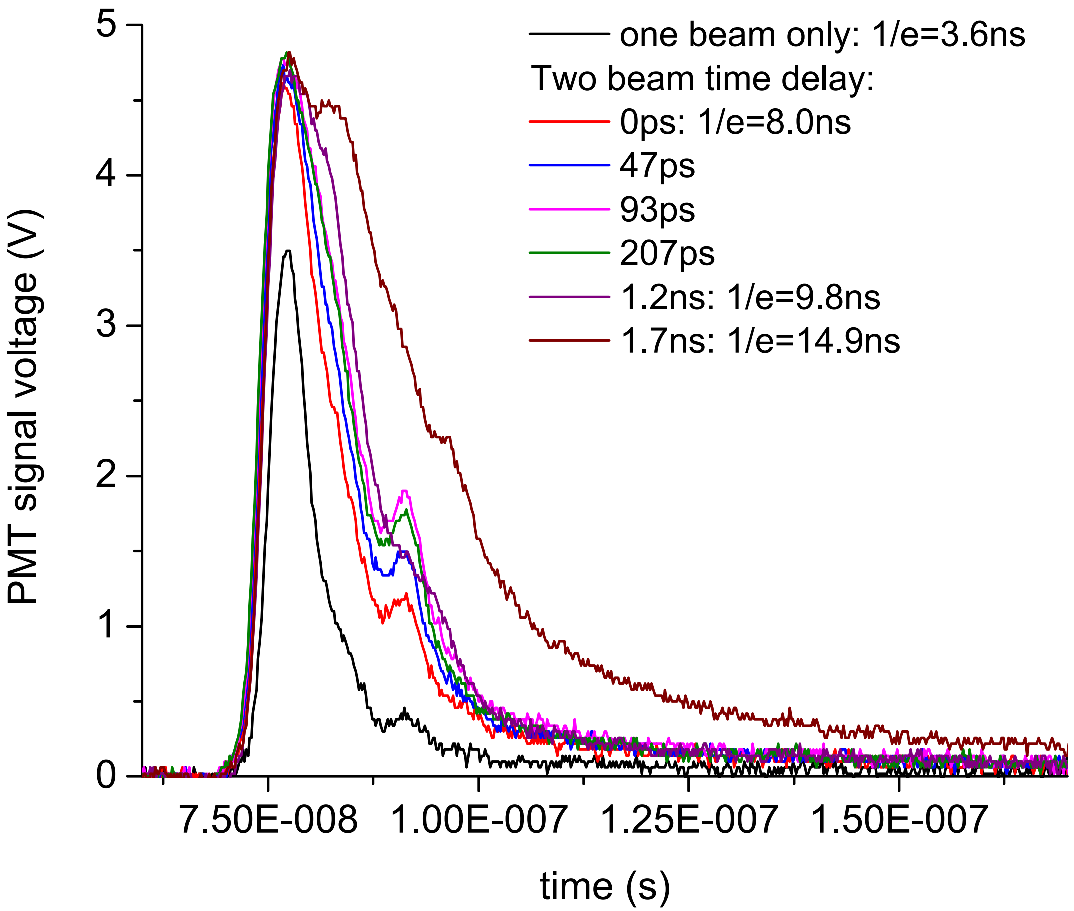
Plasma Improvement Method: Multiple Delayed USP

- Two USP with 3mJ energy each have been focused with an f=25cm lens at various time delays.
- PMT signal increases and widens as 2nd pulse is added.
- Slight increase in signal width can be observed for $\Delta\tau$< 1.2ns.
- Noticeable plasma lifetime extension for $\Delta\tau$>1.5ns



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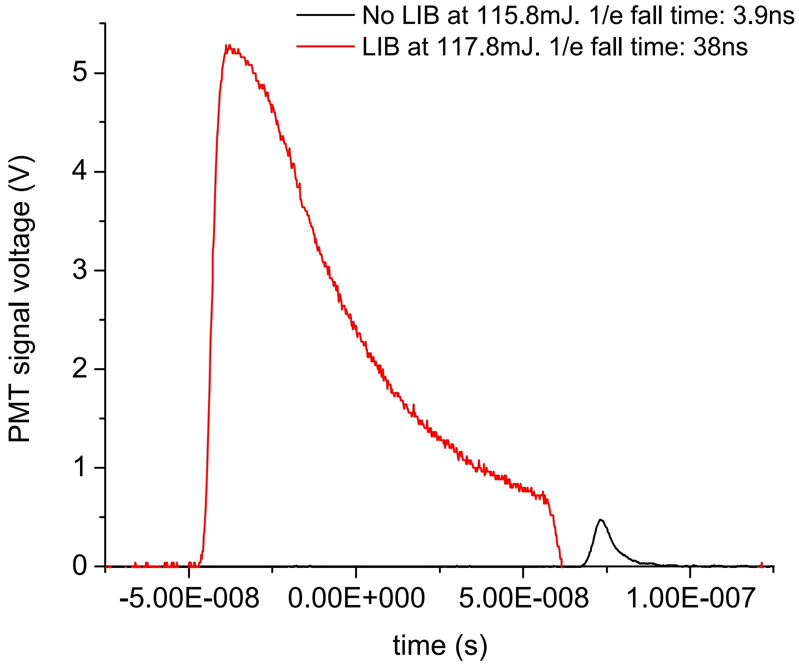
Plasma Improvement Method: nanosecond Pulses

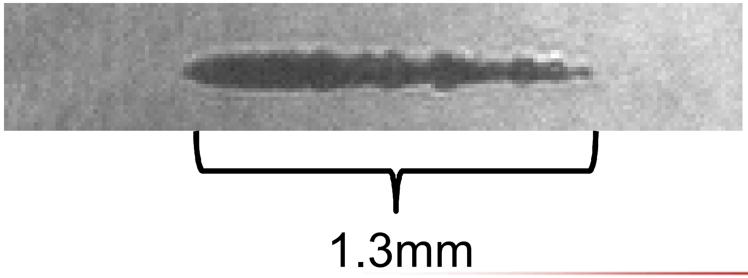
- Looking at plasma lifetime of 532nm, 8ns FWHM laser only.

- There is no laser induced breakdown (LIB) in air at an energy of 115.8mJ. Minor ionization occurs at the time scale of the temporal peak of the ns pulse (4ns FWHM).

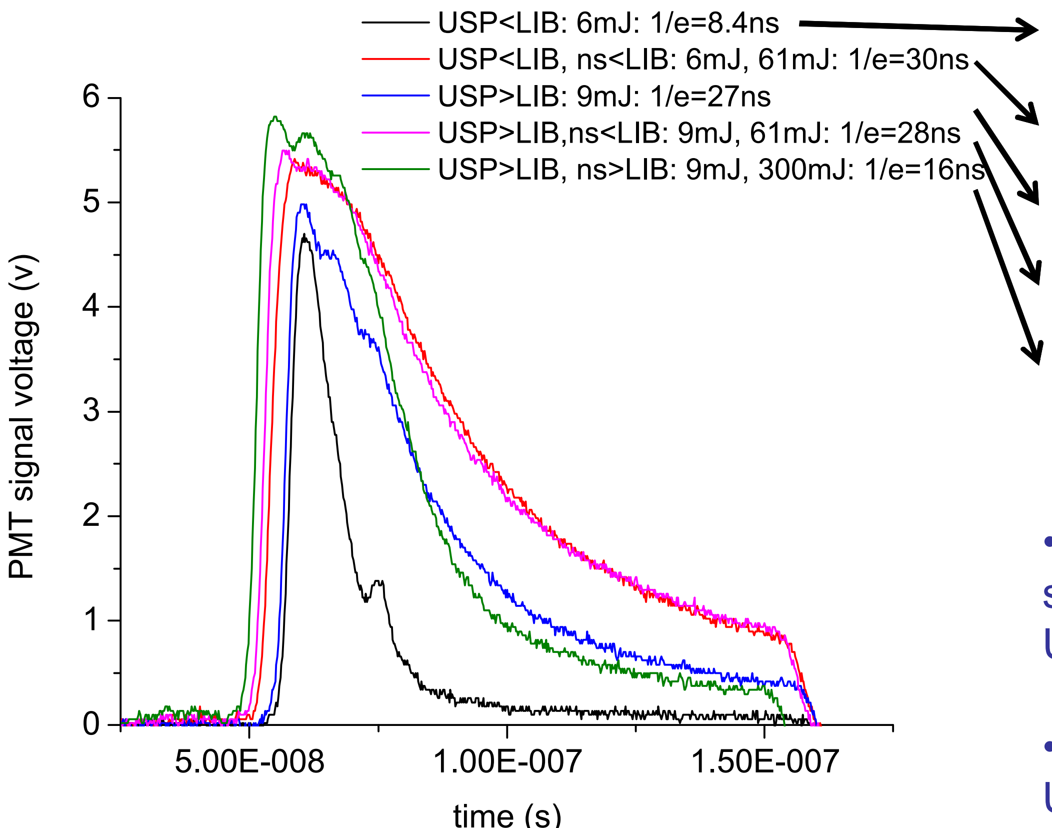
- At 117.8mJ there is clear sign of LIB. The focal region is fully ionized and decays in about 40ns.

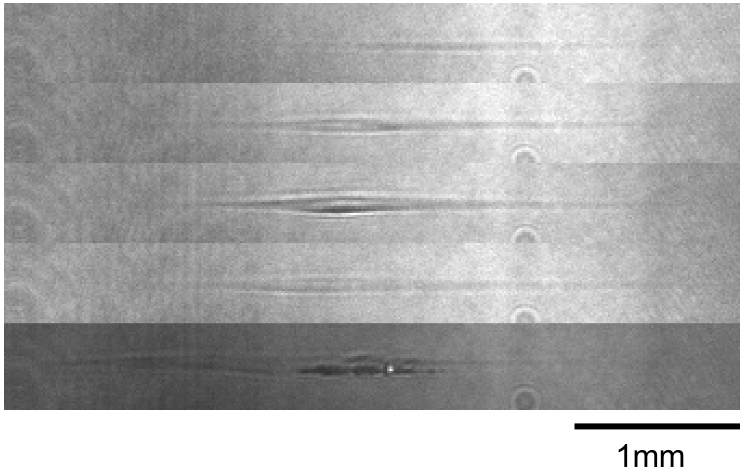
- No plasma spark is visible below LIB. At just 2mJ additional energy, the fully ionized plasma is clearly visible.





Plasma Improvement Method: USP + nanosecond Pulses





- Plasma lifetimes are longest for USP seeded ns combination regardless of USP energy above or below USP LIB.

- Highest electron density reached with USP seeded ns pulse above ns LIB. However, the electron density is so high that the electrons recombine in half the time compared to ns below LIB.

- For USP only, the electron density and life-time is higher for above LIB versus below LIB.

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Conclusions

• We have presented a comprehensive experimental approach for diagnostics of laser plasma interaction.

• Basic dynamics of short and long pulse laser plasma interactions have been studied. More elaborate parametric scans are pending.

• Multiple approaches have been presented that will prolong plasma lifetime as well as plasma channel length.

• These plasma improvement methods could be combined with each other.

• Additional methods, such as using axicons, should be explored in the future.