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Synergistic Effects of 1064nm Picosecond Pulses and nanosecond Pulsed Electric Fields on Optical Breakdown Thresholds

10 Sept 2018

Zachary Coker, CRFP

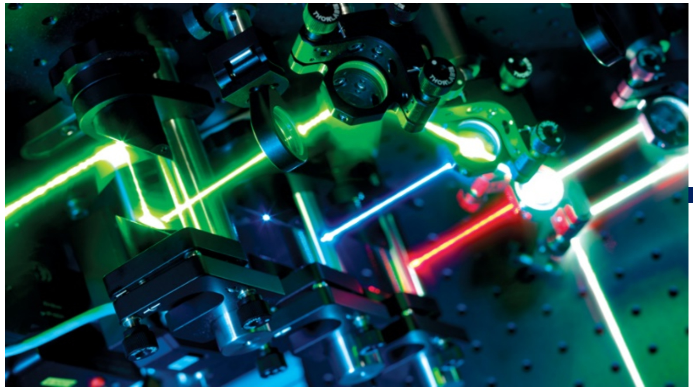
711 HPW/RHDR

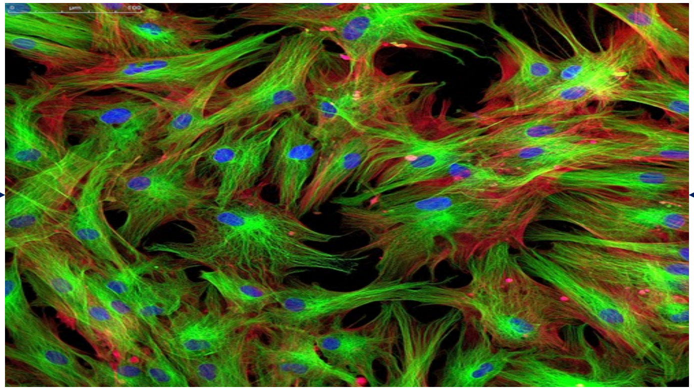
Bioeffects Division

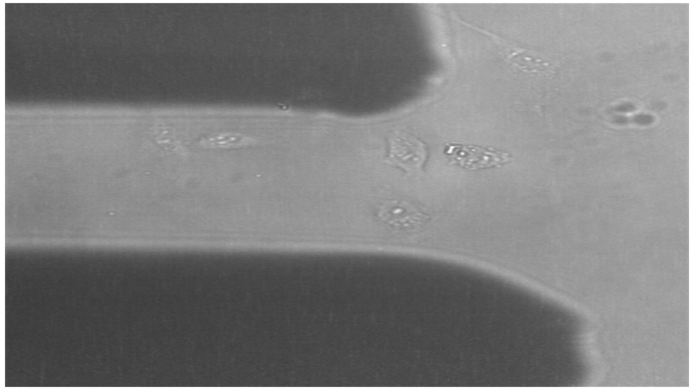
Integrity ★ Service ★ Excellence

Hypothesis

- **Optical breakdown thresholds are influenced by the presence of externally applied nanosecond pulsed electric fields (nsEPs)**
  - **Influence of electric field leads to easier cascade/avalanche ionization in condensed matter/liquids**
- **<u>Novelty</u>: first investigation into electric field interactions with optical breakdown thresholds on a cell-level study, particularly with cell-level applications & nsEP**







Overview

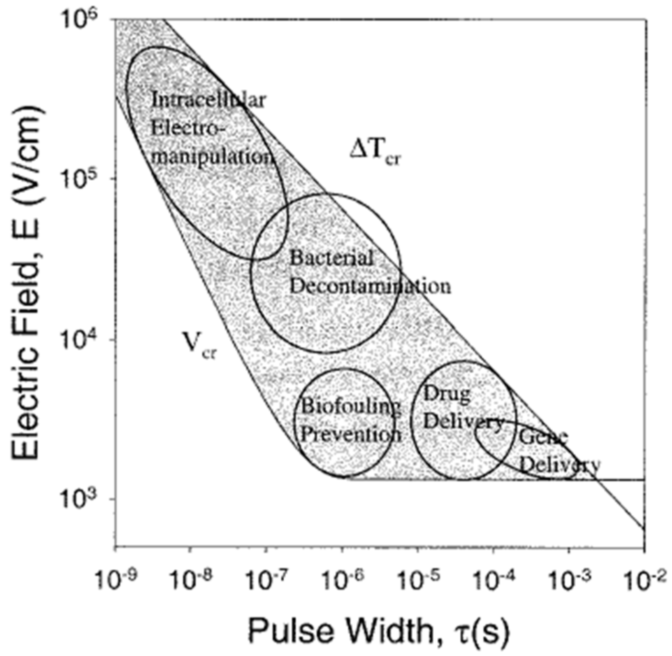
- Brief introduction to concepts of nsEP and optical breakdown
- Overall goal: answer an underlying question about Physics & interaction of nsEP with optical pulses → future applications
- Design of experiment: “what” and “how”
- Preliminary results
- Technical challenges and efforts to overcome them
- Current results
- Observations and future direction

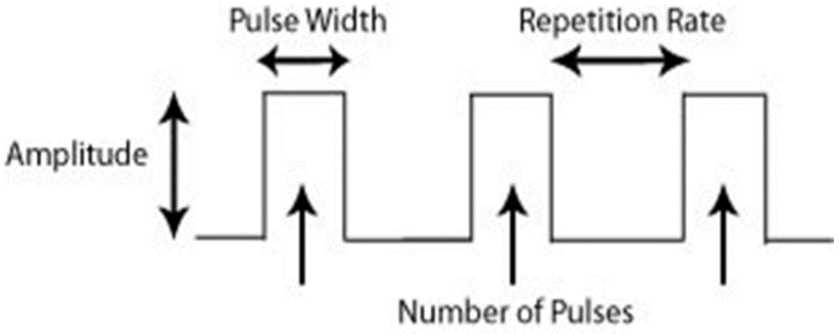
Nanosecond Electric Pulses (nsEP)

What is a nanosecond electric pulse (nsEP)?

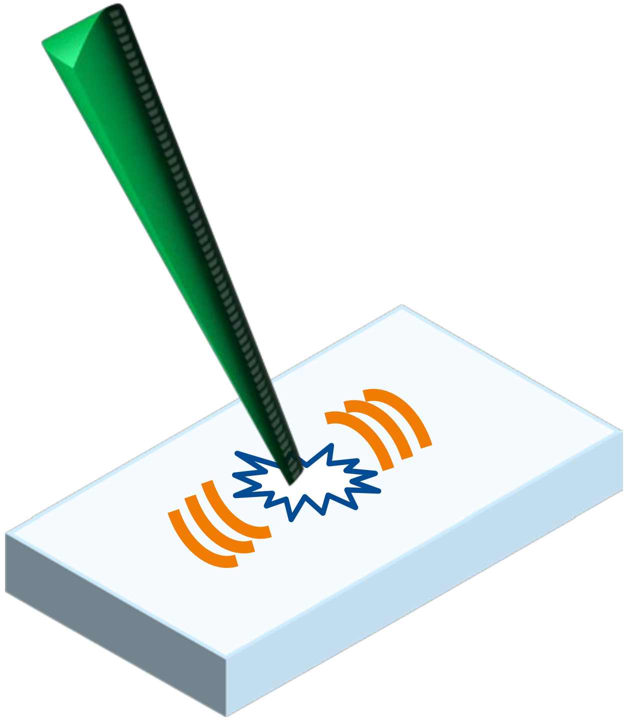
- nsEP
  - are pulses with a pulse width of less than 1 μs and
  - are generated by a large discharge of voltage across a gap, typically delivered between two metal surfaces

- Possible experimental variables
  - Pulse width
  - Amplitude (electric field)
  - Pulse number (multiple pulses)
  - Mono/bi-phasic
  - Repetition rate





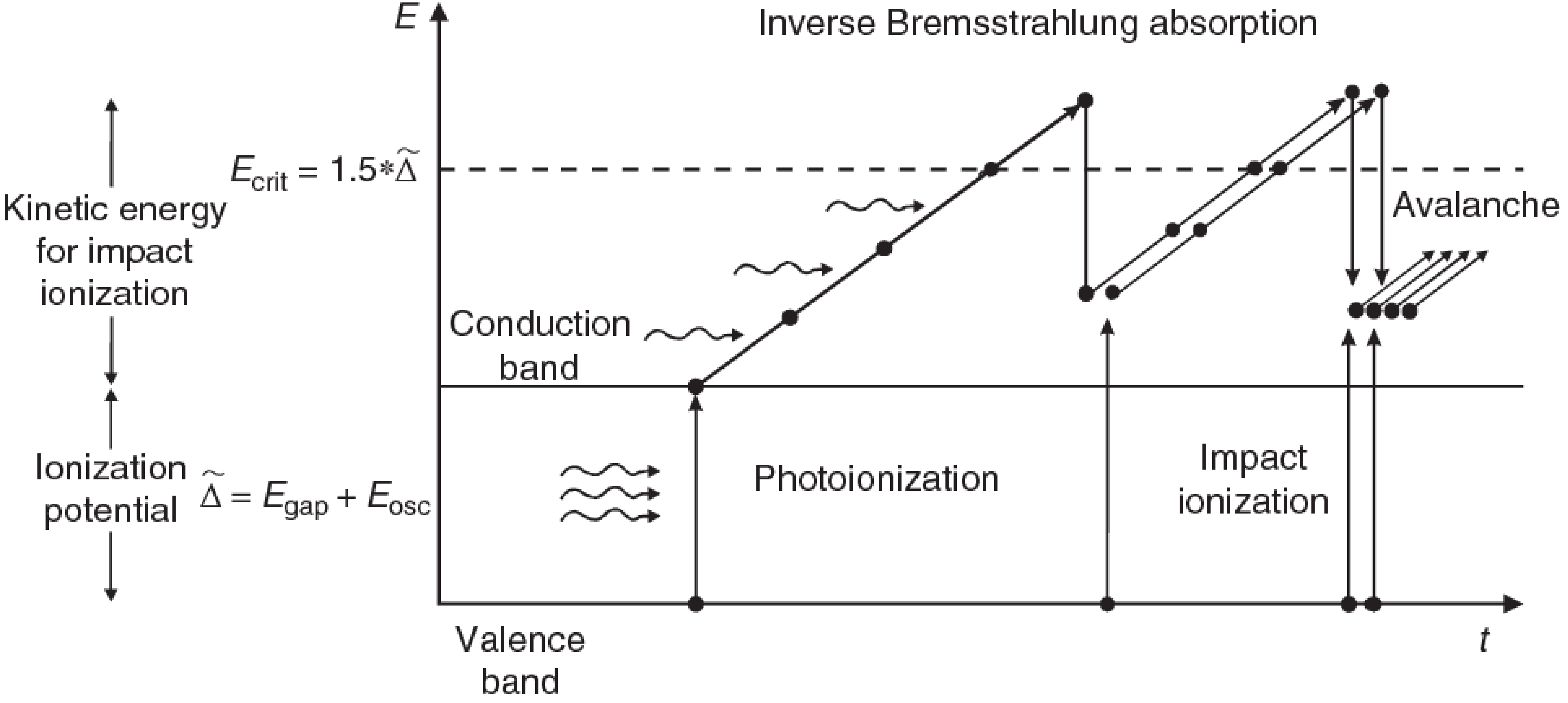
Optical Breakdown & Photoionization



- What is optical breakdown?
  - Partial or complete ionization of a material by high-intensity laser irradiation/energy absorption
- Two mechanisms lead to breakdown:
  - Multi-photon “deterministic” (typical of ultra-short fs pulses)
  - Cascade or avalanche “probabilistic” (ps-ns pulse duration)
    - requires free electrons in focal volume ➔ absorb energy ➔ collide and ionize atoms/molecules ➔ cascade effect of energy-absorbing electrons
  - Medium with high ionization potential require multi-photon absorption to start cascade breakdown process.
- Our case: 1064nm 6 picosecond pulse ➔ multi-photon excitation leads to cascade ionization as primary contributor to breakdown

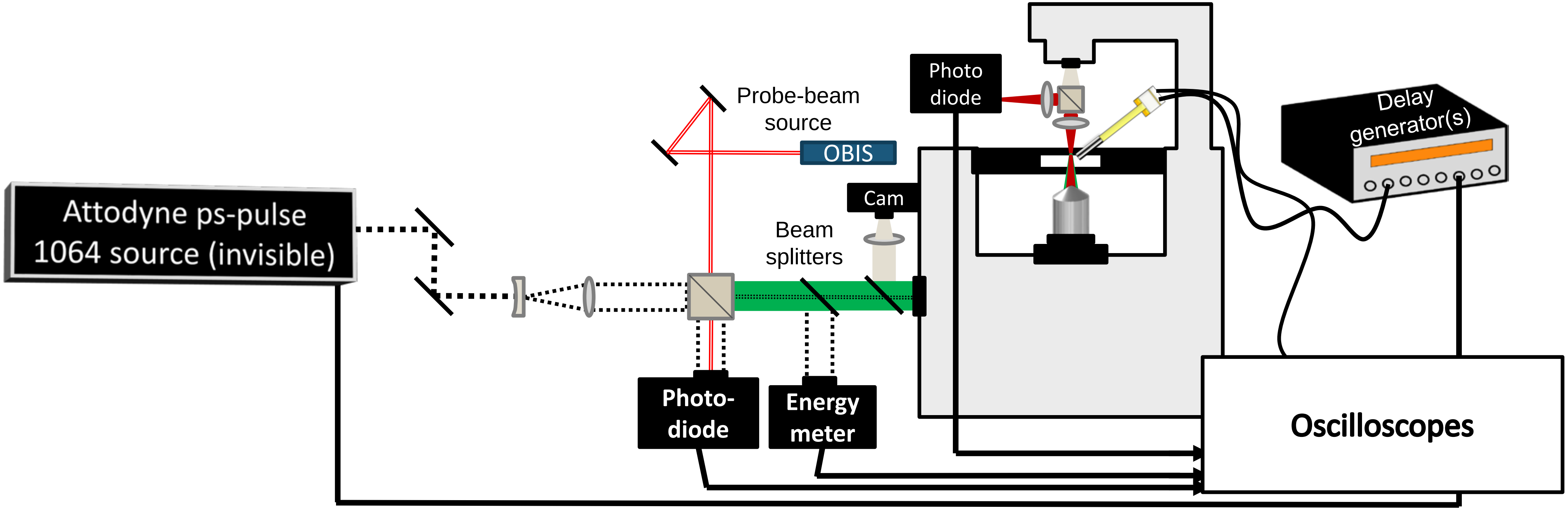
The Question & Basic Idea

Our primary question: How does nsEP affect breakdown threshold energies for optical breakdown in aqueous media?



(PART II Mechanisms of Laser Interactions
Pedro A. Quinto-Su, Vasan Venugo palan, 2007)

Experimental setup



- Attodyne 532-1064 picosecond laser (6ps pulse duration)
- OBIS 632nm probe laser
- Leica DMI4000B microscope
- 20x 0.4NA objective
- Stanford SRS DG535 delay generator (x2)
- Tektronix TDS 3054C Oscilloscope (x2)
- HP E3630A DC power supply
- 1kV high-voltage power supply
- ONDA hydrophone + pre-amp
- Custom nsEP electrode-probes
- Photo-diodes (2x)

Experiment & Detection Methods

Beam splitter to photo-diode for breakdown detection

nsEP electrodes

nsEP probe to oscilloscope

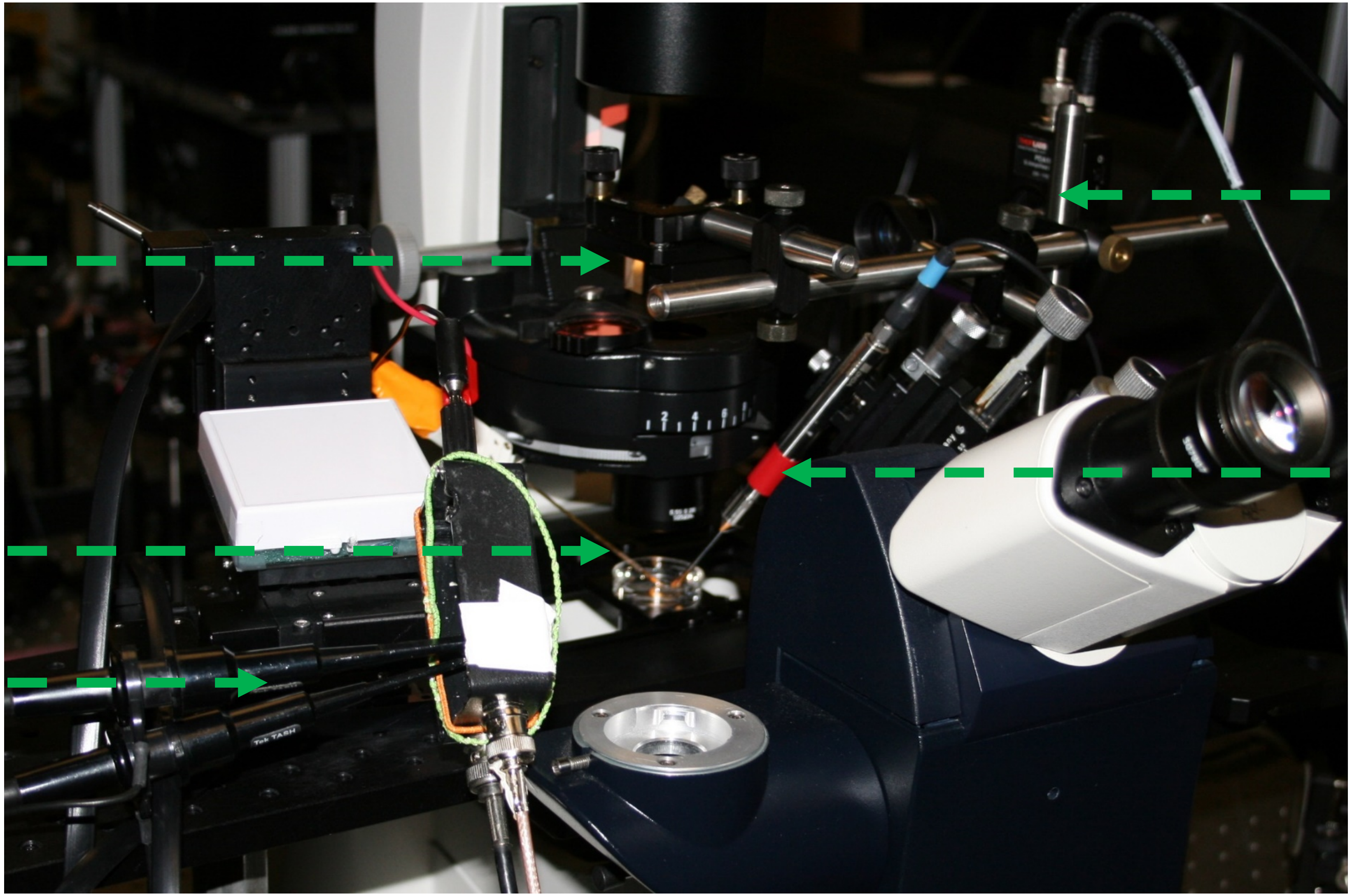


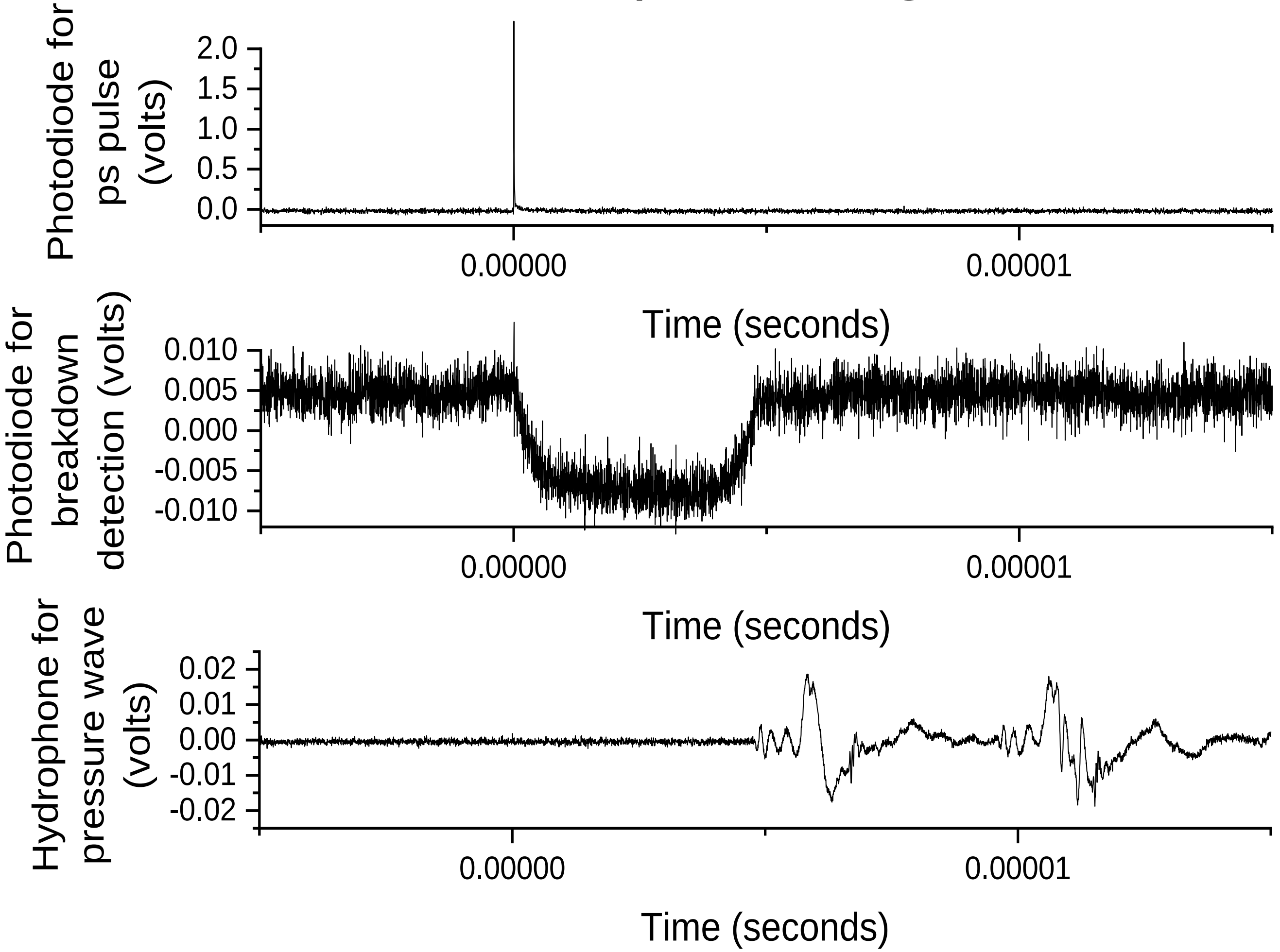
Photo-diode for breakdown detection

Hydrophone for breakdown pressure-wave detection

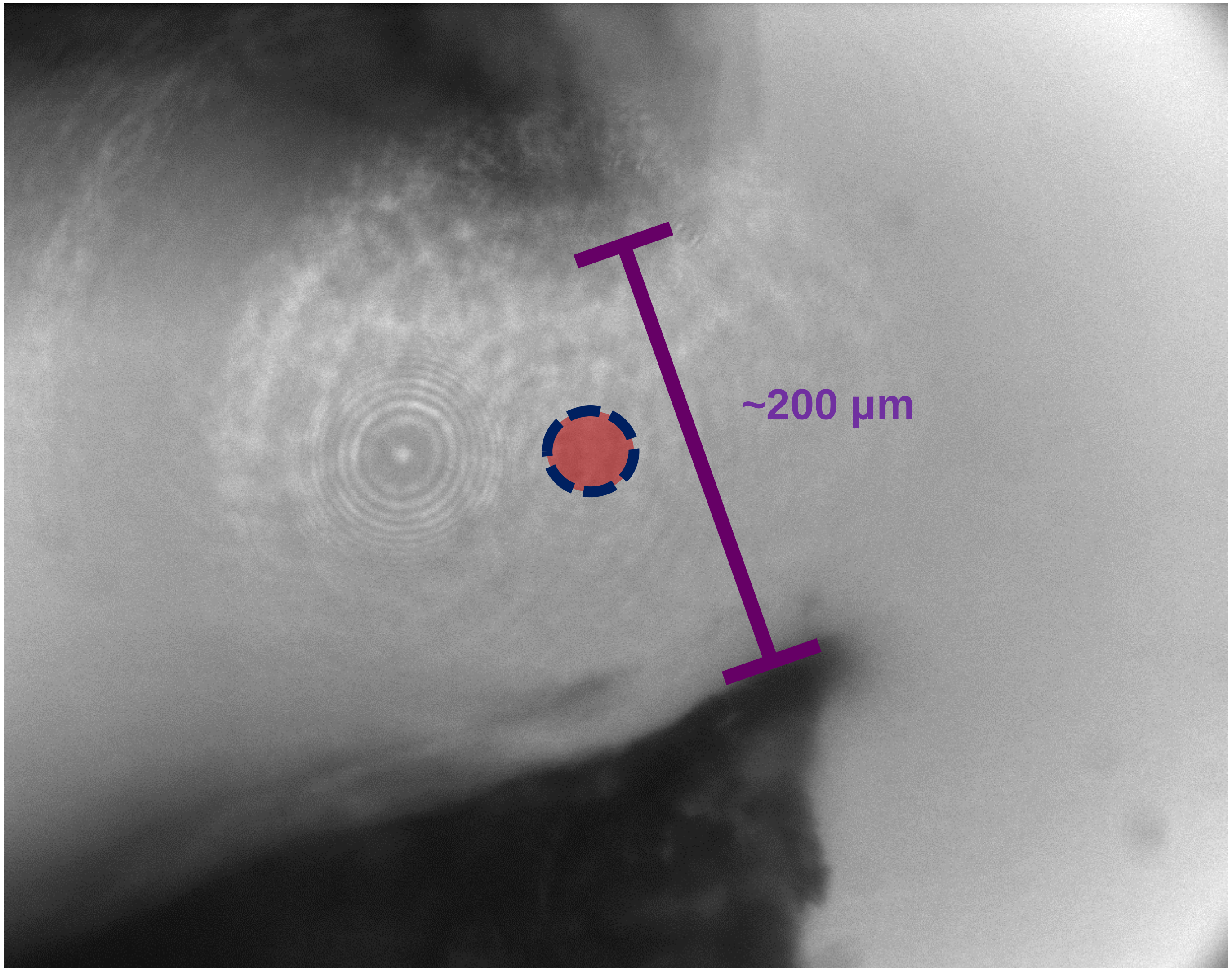
Optical Pulse and Breakdown Detection

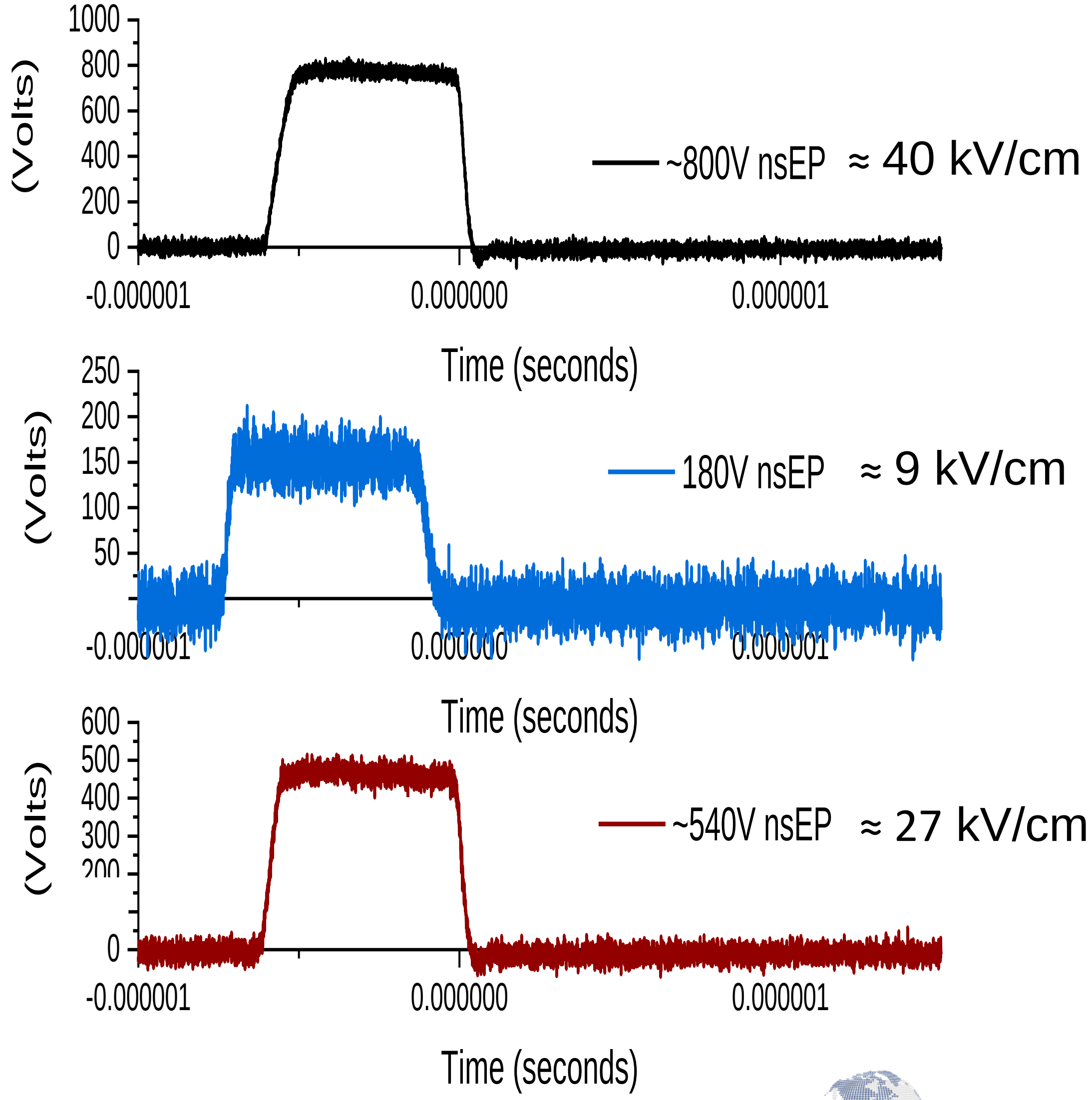
- Delay generator triggers a 600ns nsEP pulse (measured on separate oscilloscope)
- 100ns later, triggers 6ps optical pulse
- 6ps pulse detected by 1st photodiode and triggers second oscilloscope
- Optical pulse passes through sample causing breakdown
- Probe beam deflected by breakdown event, and measured on scope breakdown diode
- μs later, hydrophone measures pressure wave

Oscilloscope readings

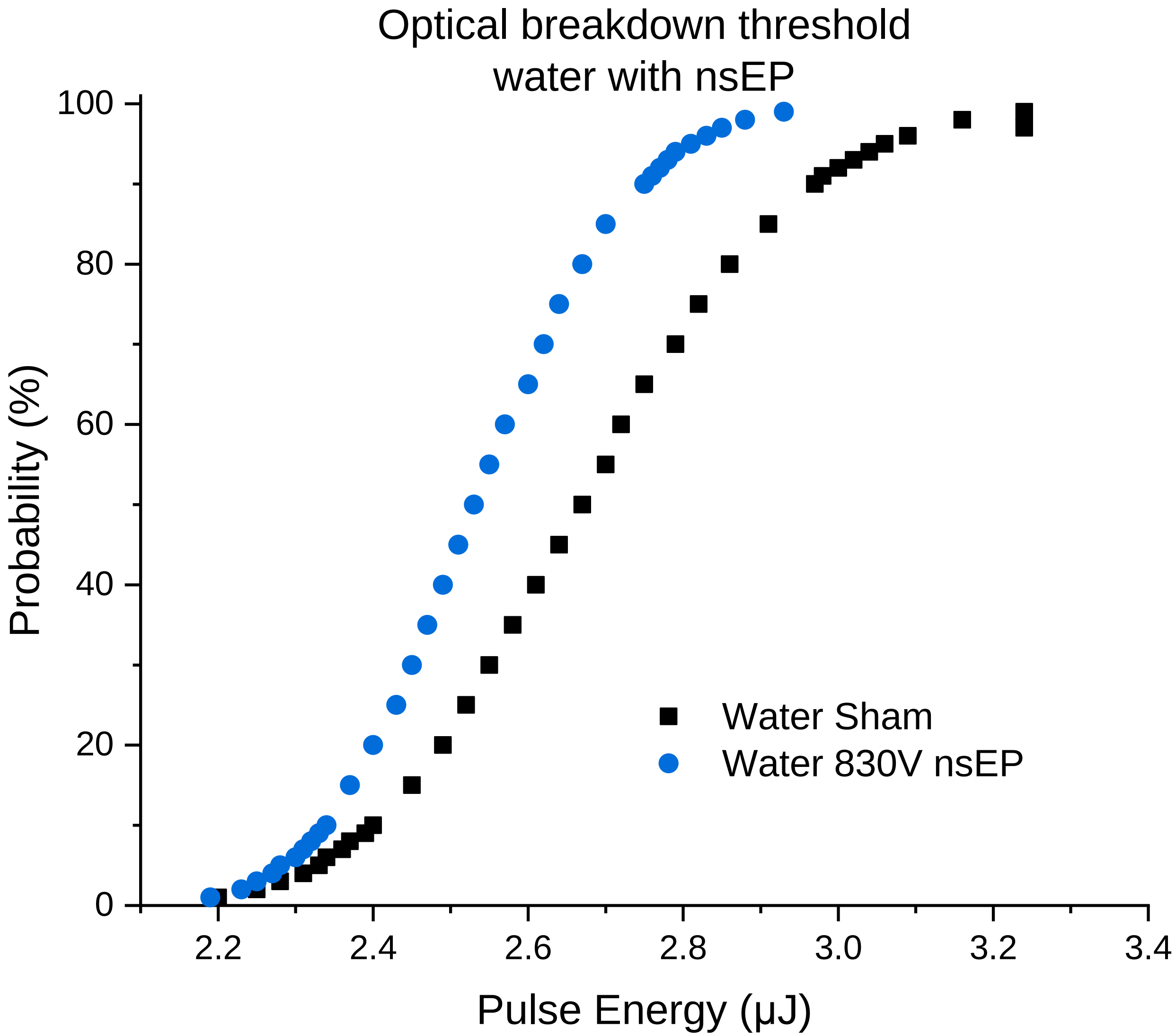


Sample View, nsEP Pulse and Laser Focus





Preliminary Results

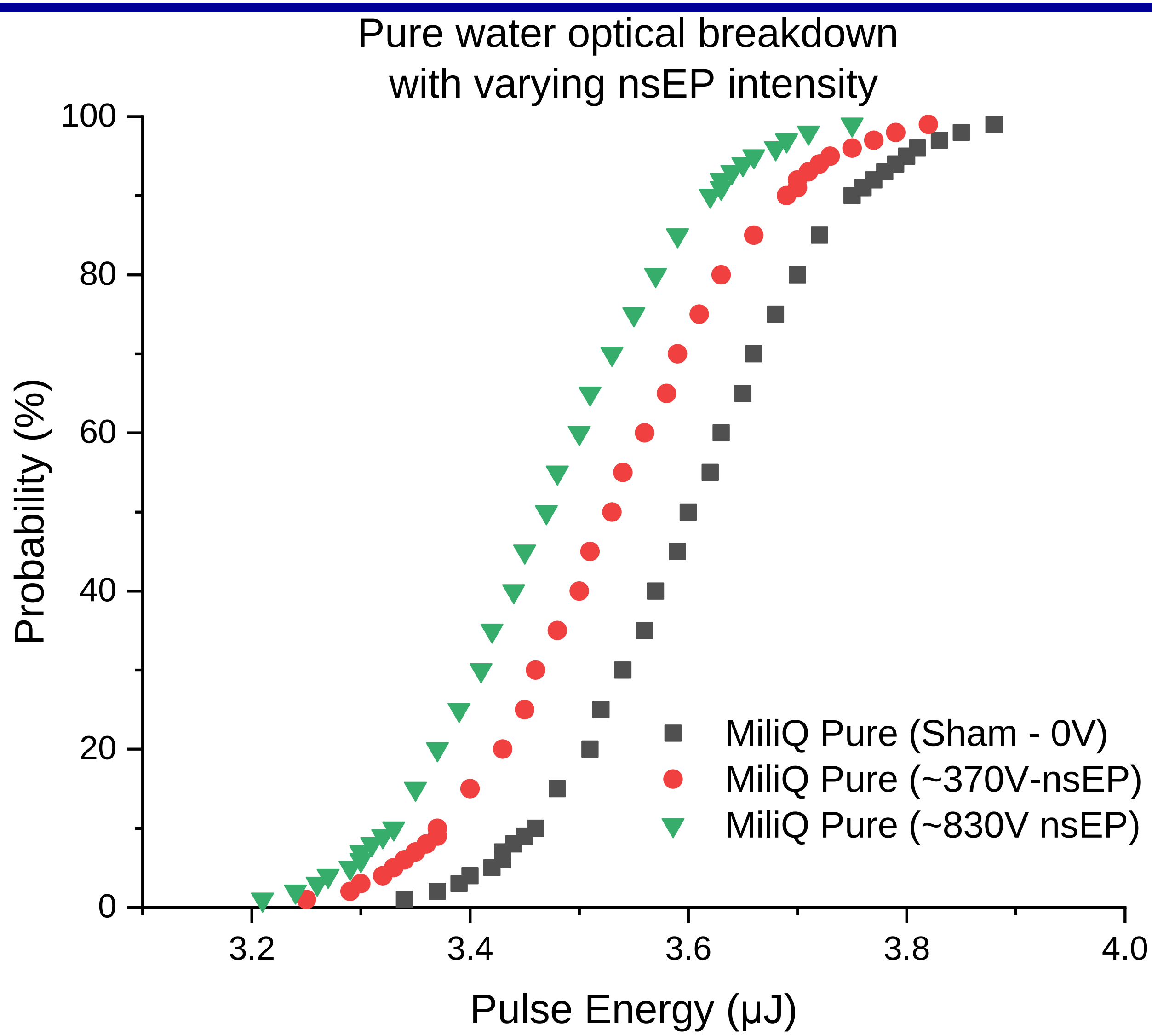


- **Tested aqueous solutions relevant to cell culture experiments**
- **nsEP appears to "shift" breakdown probability curve vs pulse energy**
- **Hydrophone used to initially detect breakdown could be damaged by nsEP**
- **All-optical system desirable to prevent damage to elements**

Initial Observations & Technical Complications

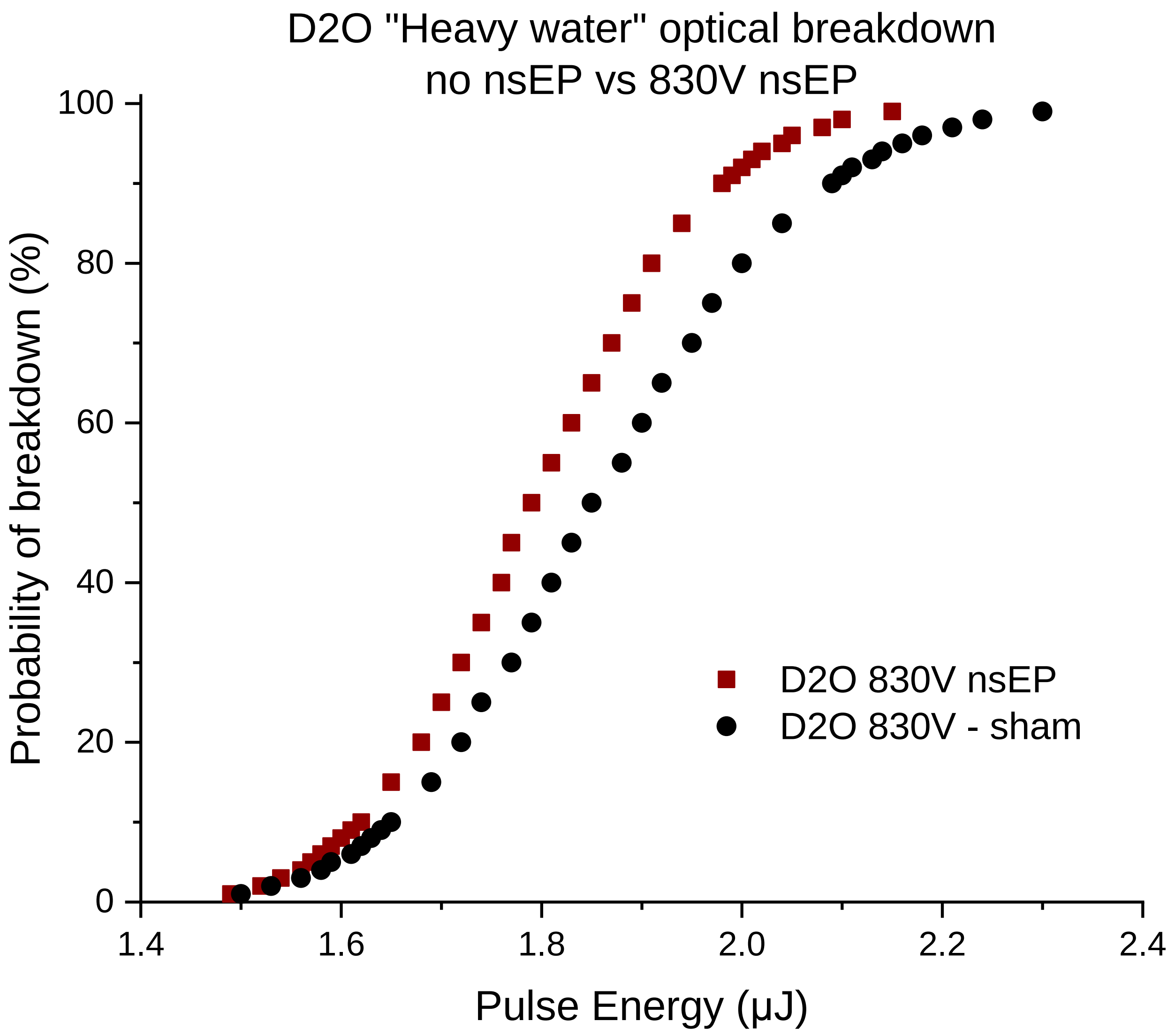
- Optical breakdown occurred at the lowest power/energy settings for the laser
- Laser output appeared to vary day-to-day
  - Need more reliable attenuation and energy detection
  - Possible there are daily changes in laser mode quality or polarization (unknown)
- All-optical detection desired to avoid damaging hydrophone with nsEP pulse
- Complex solutions could behave differently compared to “simpler” solutions
  - Lead to testing of pure water and D_2O “heavy water” to compare like-samples
- Hypothesis: Electric field intensity will have direct impact on results

Breakdown in "Pure Water" & Dependence on nsEP Intensity



- **Mili-Q purification system**
  - **18.2 MΩ pure water**
  - **Higher threshold energy compared to regular water (2.2-3.2 µJ v 3.2-3.9 µJ)**
- **Again, nsEP appears to "shift" breakdown probability curve vs pulse energy**
  - **nsEP intensity dependent**
  - **Greater shifts correspond to greater field intensity**
  - **Could correspond to increased electron mobility and kinetic energy**

Breakdown in D_2O "Heavy Water" With nsEP



- **Heavy water breakdown significantly lower than pure water**
  - **(1.5-2.3 µJ vs 3.2-3.9 µJ)**
  - **Causes not yet identified**
- **Purity likely not the reason, as heavy water ~99.9% pure**
- **Possibly related to energy band gaps or increased multiphoton ionization**
- **Heavy water approximately full order of magnitude less absorption at 1064nm**

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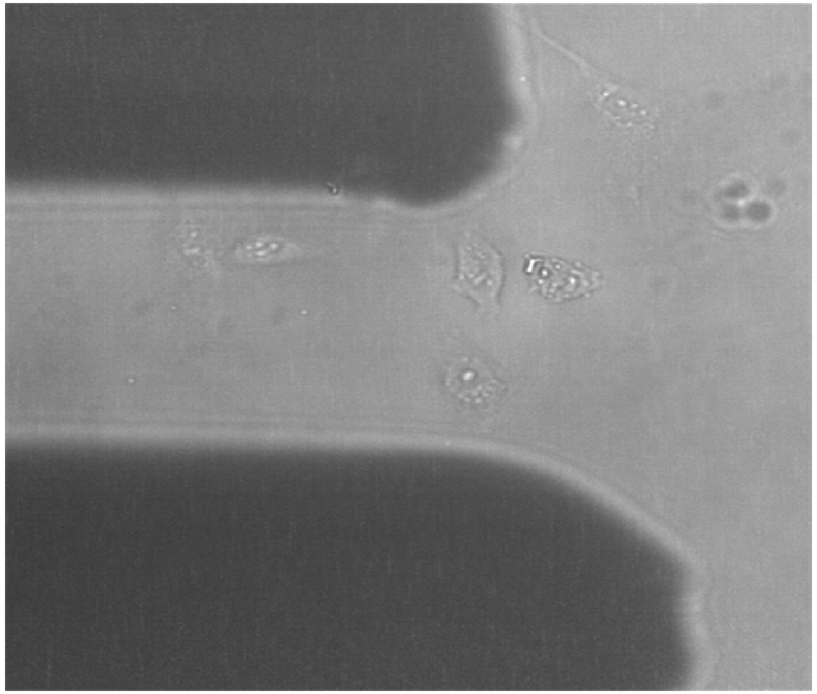
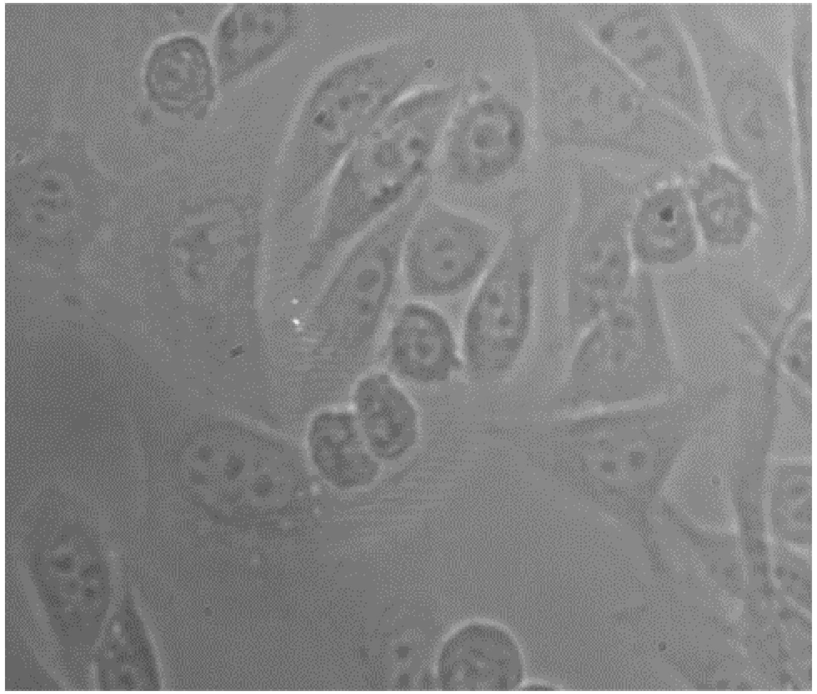
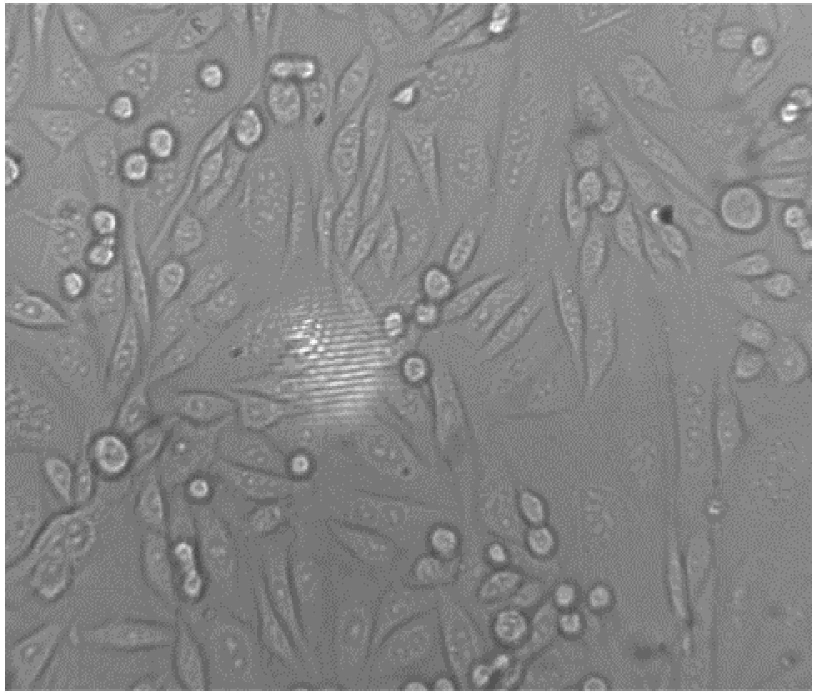
Current Observations

- Optical breakdown thresholds reduced by nsEP of all strengths
  - Increased voltage = increased effect (nominally in some samples; lower-V)
- Substantially different between pure water and heavy water tested
  - Likely due to impurities in regular water, and chemistry of “heavy water” (?)
    - Increased probability for cascade from impurities in regular water
    - Increased multi-photon ionization in heavy water (?)
- Laser pulse energy varies pulse-pulse
  - Energy meter set up to measure each individual pulse (by ratio T:R)
  - Optimizing polarization & clean-up before beam-combining should help
- All-optical detection with probe-beam deflection and photo-diode
- Future work to implement cell-level studies similar to nsEP poration studies using uptake of nano-dye Yo-Pro and Propidium Iodide

So What's Next?

Future application to cellular-level studies:
Synergy below thresholds?

Combined Optoporation & Electroporation

- **Optoporation: transient perforation in a cell membrane is made using focused ultrashort laser pulses**
- **Electroporation/electropermeabilization: electric field applied to cells in order to increase the permeability of the cell membrane**
- **Investigating the synergistic effects:**
  - **Can we use these two techniques for targeted/specific purposes?**
    - **Electro-optic poration: inhibition or discrete localization?**

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