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Optical and Electrical Diagnostics of a High-Voltage Laser-Triggered Switch with Variable Impedance Load

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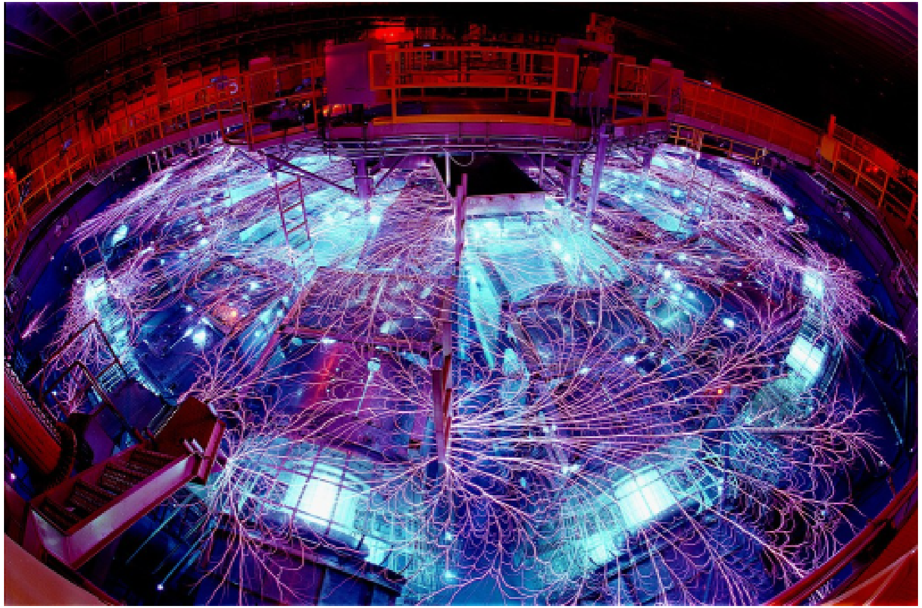
Introduction to Pulsed Power

- kV to MV potentials kA to MA currents
- Hundred Nanosecond scale pulses
- High-Voltage Laser-Triggered Switch
  - Time Repeatability and Jitter ~ nanoseconds
  - Single Laser, Many Switches
- Used to produce extreme temperatures and pressures
  - High Energy Physics
  - Fusion



Sandia National Labs Z Machine
Credit: https://www.sandia.gov/z-machine/

Theory

Braginskii model power balance [1]:

$$\frac{I}{\sigma} = 2\pi^2 \rho_0 \xi (a\dot{a})^3$$

Martin Model [2]:

$$a^2 = \left(\frac{4}{\pi^2 \rho_0 \xi \sigma}\right)^{\frac{1}{3}} \int_0^t I^{2/3} dt \qquad R_{Plasma} = \frac{L}{\sigma \pi a^2}$$

Spitzer Resistivity [3]:

$$\eta = \frac{1}{\sigma} = \frac{2\sqrt{2\pi}}{3} \frac{Ze^2 \sqrt{m_e} \ln \Lambda}{(4\pi\varepsilon_0)^2 (k_B T_e)^{3/2}}$$

I – Current

σ – Plasma Conductivity

η – Plasma Resistivity

ρ_0 – Gas Density

ξ – Dimensionless Constant

a – Plasma Channel Radius

$\dot{a}$ – Rate of Plasma Channel Radial Growth

L – Plasma Channel Length

e – Elemental Charge

m_e – Electron Mass

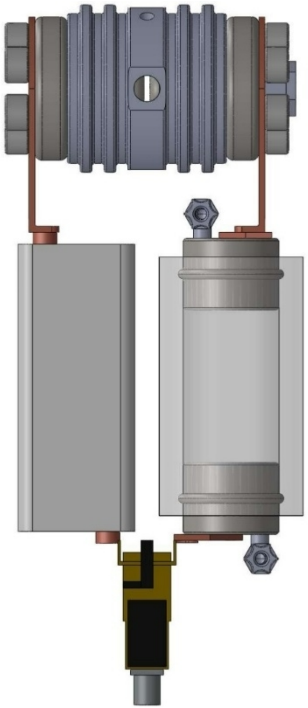
$\ln \Lambda$ – Coulomb Logarithm

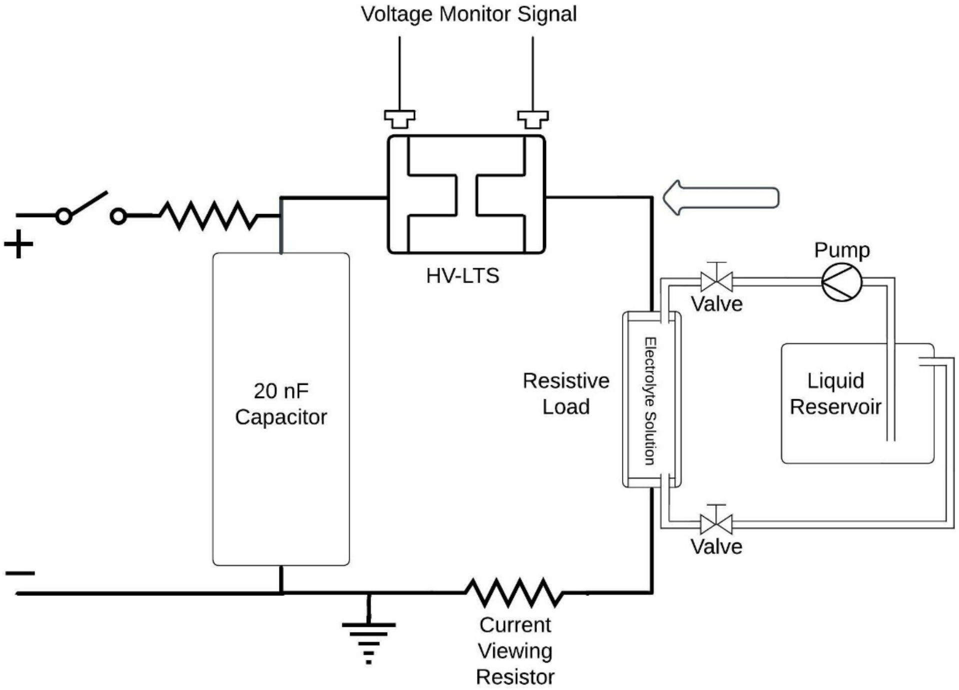
T_e – Electron Temperature

[1] Braginskii, S., “Theory of the Development of a Spark Channel.”
[2] Martin, T. H., et al., “Energy losses in switches.”
[3] Spitzer, L., Härm, R., “Transport Phenomena in a Completely Ionized Gas”

High-Voltage Switch Testbed with a Variable Impedance Load

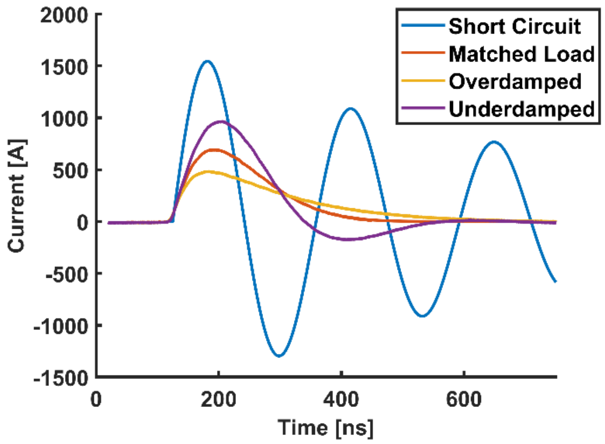
- 3.5 mm Spark-Gap
- Ambient Pressure & Temperature
- 5 – 6 kV Operation
- Tunable Load
  2 – 10 Ω

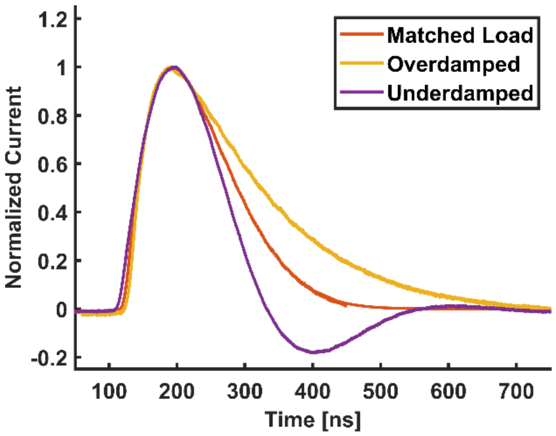




High-Voltage Switch Testbed with a Variable Impedance Load

- Impedance is Tuned to Switch Conditions
- Rising-Edge Determined by Pulse Forming Network

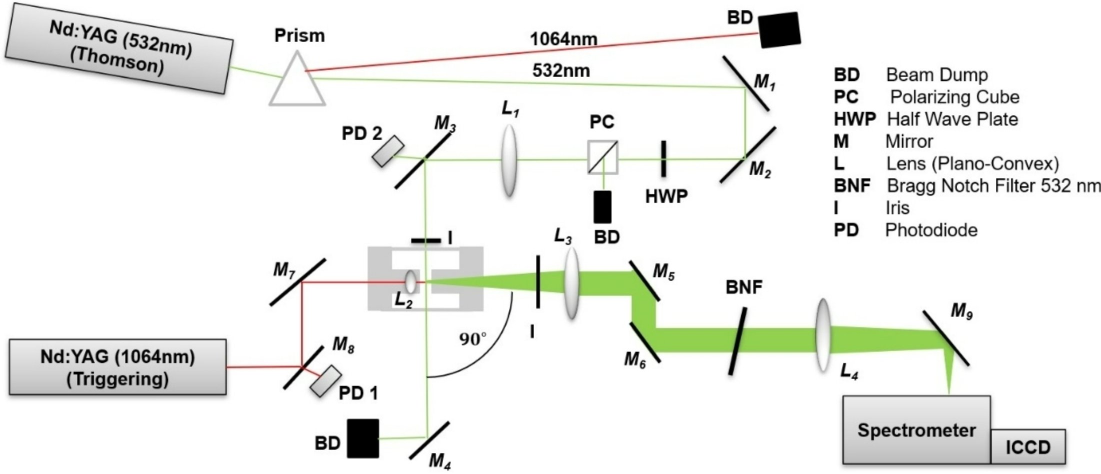




Time Zero is defined by the time of the triggering laser pulse

Experimental Design – Laser Thomson Scattering

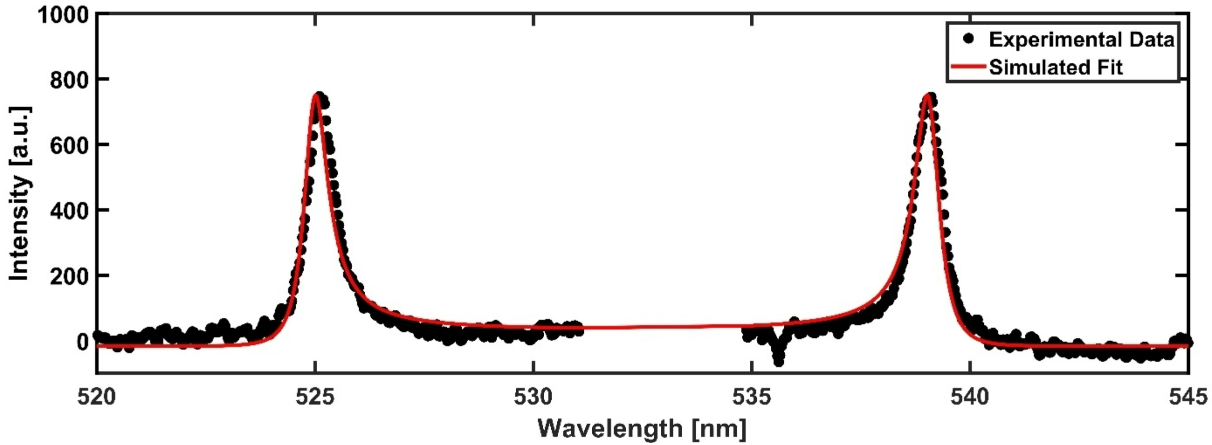
- Laser Thomson Scattering
  - Electron Temperature (Plasma Conductivity)
  - Electron Density
- No Assumptions Needed



Experimental Design – Laser Thomson Scattering

Salpeter Approximation Ignoring Ion Contribution

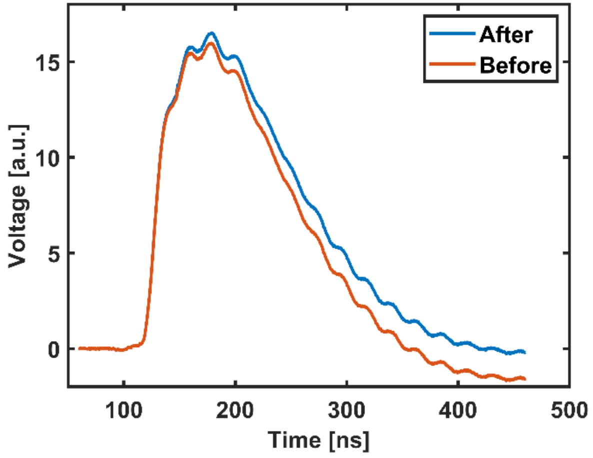
$$S(\mathbf{k},\omega) \approx \frac{\sqrt{2\pi}}{v_{te}} \Gamma_\alpha(\xi_e)$$



Experimental Design – Electrical Diagnostics

- Non-contact Derivative Coupled Voltage Monitors (V-Dot Probes)
- No Affect on Switch Performance
  - No Path to Ground
- Require Integration
  - Numerical
    - Oscilloscope May Alias High Frequency Data
  - **Analog RC Circuit Integrator**
    - Requires Droop Correction

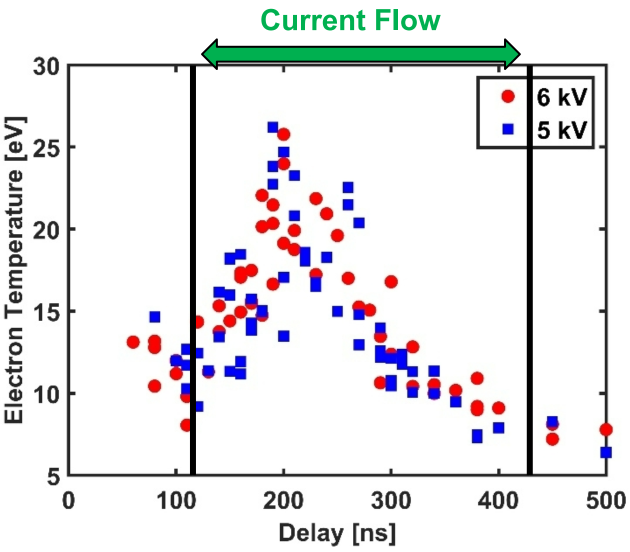
$$S(t)_{corrected} = S(t) + \frac{3}{2\tau}\int_{t_{start}}^{t} S(t')\,dt'$$



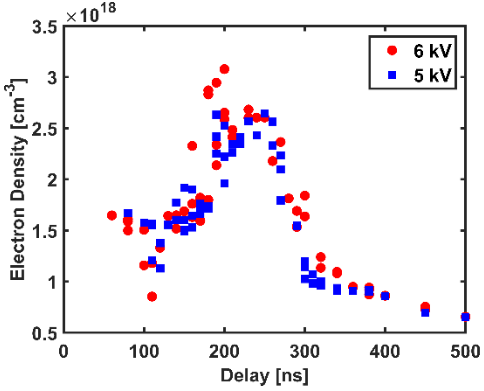
Results – Optical Diagnostics

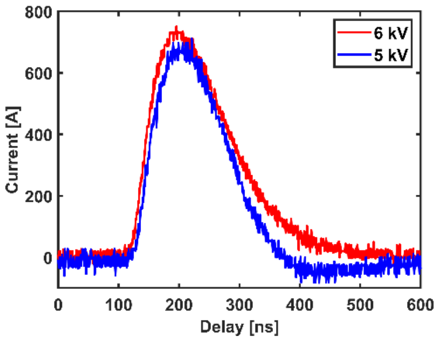
Laser Thomson Scattering

- **Electron Temperature Does Not Stabilize**
- **Changing Plasma Conductivity**



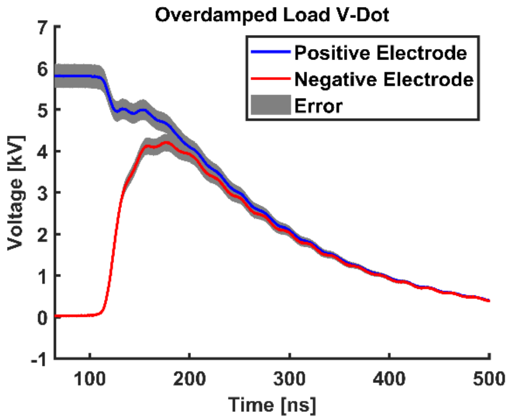
± 20% Error

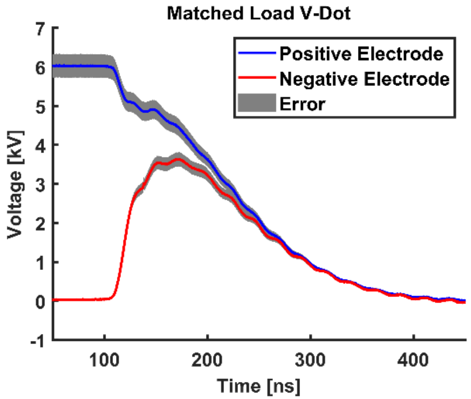


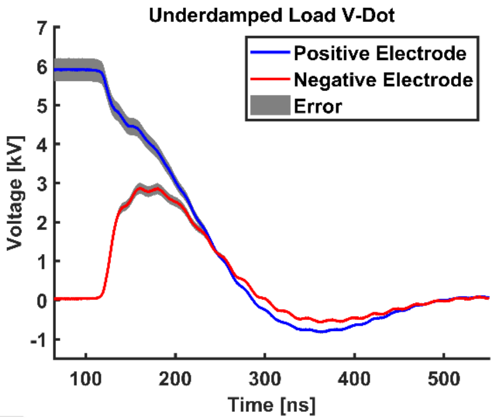


Results – Electrical Diagnostics

- Capacitor Charged to 6 kV
- Load Impedance Changed





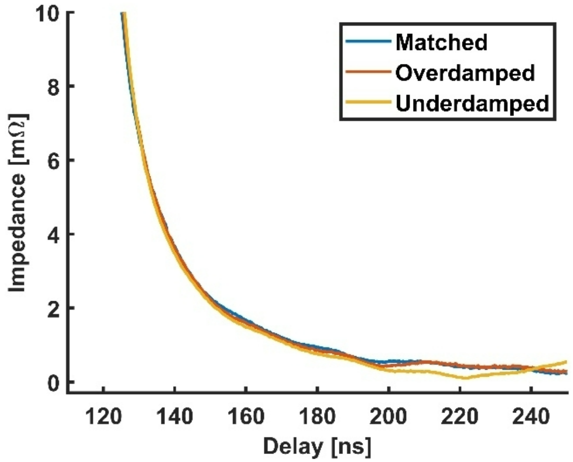


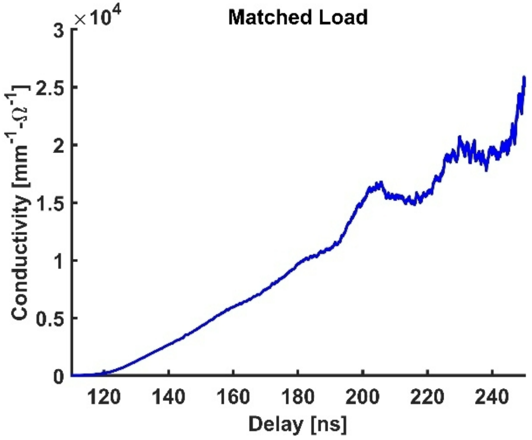
Results – Electrical Diagnostics

- Plasma Channel Impedance Collapse Determined by Pulse Forming Network (Not Load)
- The Plasma Channel Conductivity is Not Constant

$$R_{Plasma} = \frac{V_{drop}}{I}$$

$$R_{Plasma} = \frac{L}{\sigma \pi r^2}$$





Conclusion

- Optical Measurements Show a Changing Electron Temperature and In Turn The Calculated Plasma Conductivity
- Electrical Measurements Show an Increasing Plasma Conductivity During Rising Edge of Current Pulse
- Assumption of a Temporally Constant Plasma Conductivity in the Martin/Braginskii Model is not accurate for this operating regime

Acknowledgements

Sandia National Laboratory for the funding, mentorship and equipment that made this research happen

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Additional Slides

- Thomson Scattering Simulation

Gottfried, J., Rose, C., Simpson, S., and Yalin, A. “Thomson Scattering Measurement of Plasma Evolution During the Current Pulse in a Laser-Triggered Switch.” *Under Review*.

the scattering form factor, $S(\boldsymbol{k},\omega)$, is used[37,40]:

$$S(\boldsymbol{k},\omega) \approx \frac{\sqrt{2\pi}}{v_{te}} \Gamma_\alpha(\xi_e) \quad (2)$$

where the line shape function, Γ_α, is:

$$\Gamma_\alpha(\xi_e) = \frac{\exp(-\xi_e{}^2)}{|1+\alpha^2 w(\xi_e)|^2} \quad (3)$$

where the plasma dispersion function, $w(\xi)$, is[41]:

$$w(\xi) = 1 - 2\xi_e e^{-\xi_e{}^2} \int_0^{\xi_e} e^{-\zeta^2} d\zeta + i\pi^{\frac{1}{2}} \xi_e e^{-\xi_e{}^2} \quad (4)$$

where the ratio, ξ_e, of wave phase velocity to the electron thermal velocity is[41]:

$$\xi_e = \frac{\omega_{pl}}{k v_{te} \sqrt{2}} \quad (5)$$

and the electron thermal velocity, v_{te}, is:

$$v_{te} = \sqrt{\frac{8 k_B T_e}{\pi m_e}} \quad (6)$$