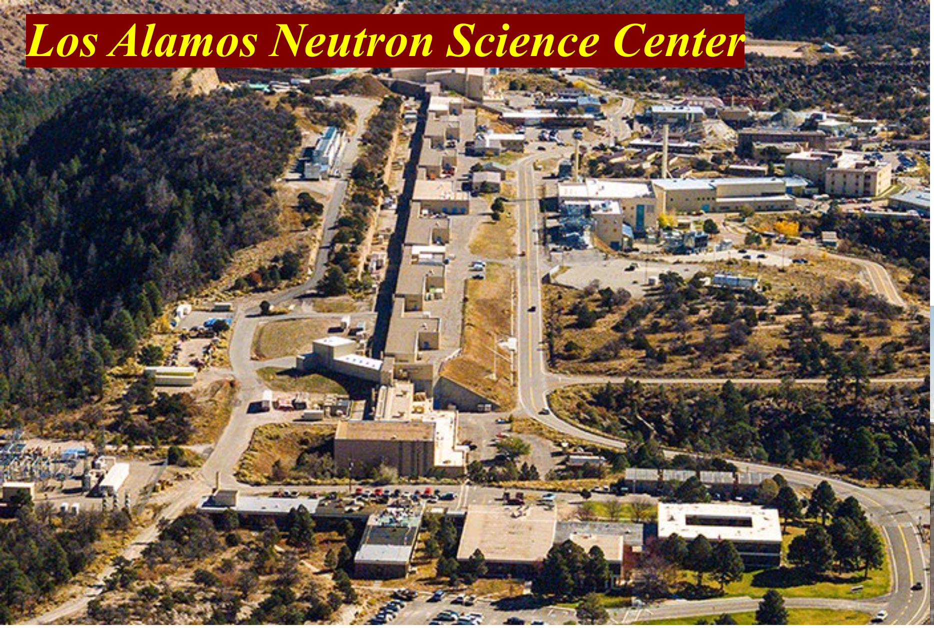

Exploring Cesium and H^- beam properties internal to the LANSCE H^- Ion Source using Resonant Absorption Spectroscopy and Cavity Ring Down Spectroscopy

David Kleinjan
Los Alamos National Laboratory (LANL)
Co-authors: Gary Rouleau, Levi Neukirch (LANL)

LANL LA-UR-22-30048

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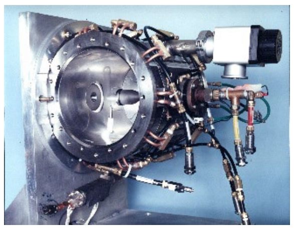
Outline

- 1.) LANSCE H- Ion Source review
- 2.) Motivation
- 3.) The LANSCE H- Ion Source Laser Diagnostic Stand
- 4.) Cs measurements using resonant absorption spectroscopy
  - *i.e.* Tunable Diode Laser Absorption Spectroscopy (TDLAS)
- 5.) Status of H- Beam density using Cavity Ring Down Spectroscopy (CRDS)

Look here for where we are in this outline

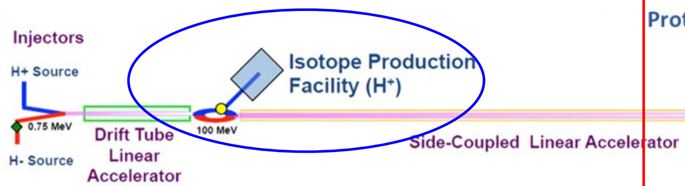
The Los Alamos Neutron Science Center (LANSCE)

H+ Ion Source

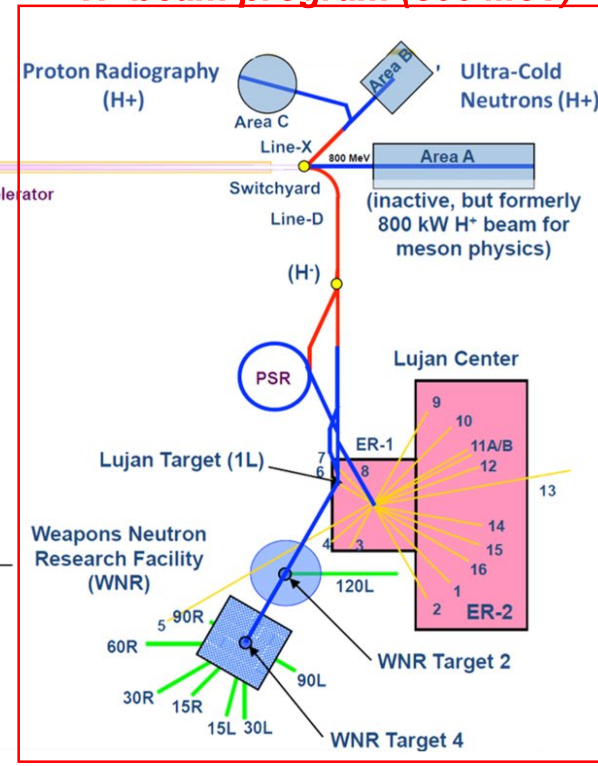


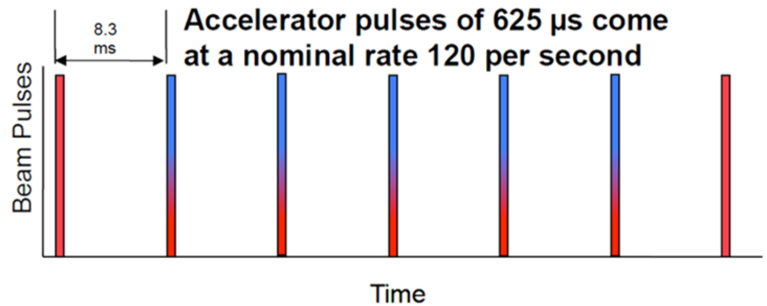
H- ion source

H+ beam program (~100 MeV)



H- beam program (800 MeV)

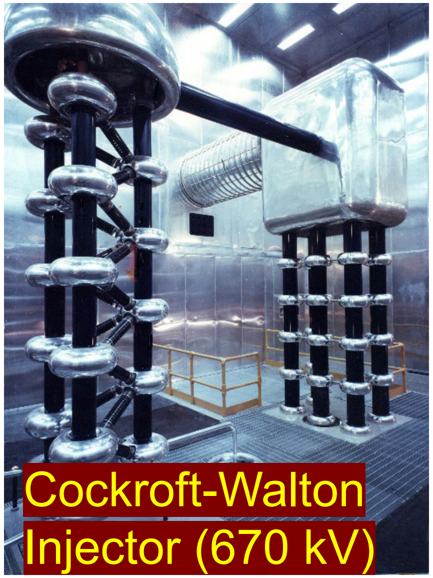


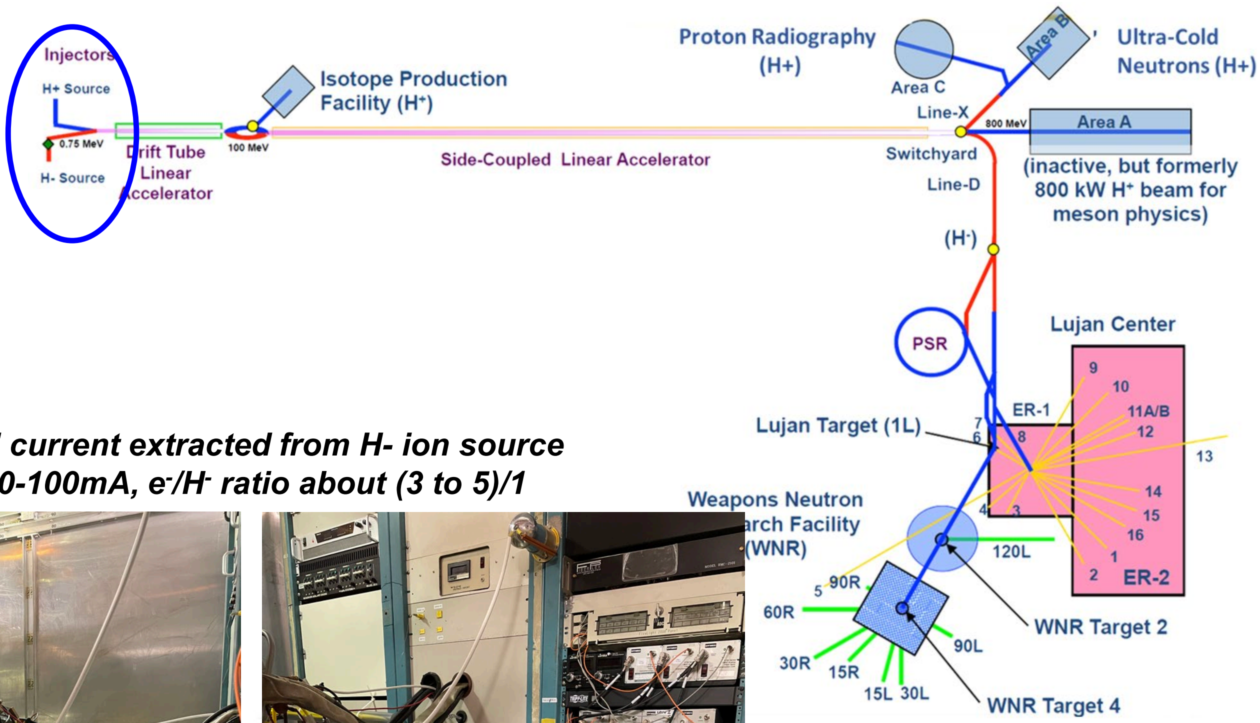


- LANSCE Dual H+ and H- beam programs
  - H+ beam one program
    - Isotope Production Facility
  - H- beam multiple programs
    - (Proton Radiography, Lujan Center, WNR, Ultra-Cold Neutrons)
- The LANSCE H- Ion Source
  - H- ion source parameters
    - 120 Hz, 10% D.F. (833µs pulse)
    - 14-16 mA of H- current
    - Ion Source recycle every 4-5 weeks

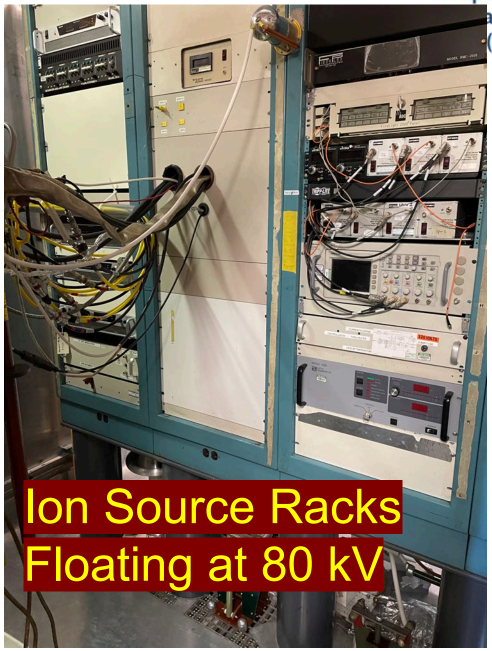
https://lansce.lanl.gov

LANSCE Front End Injection





Total current extracted from H- ion source Is ~60-100mA, e⁻/H⁻ ratio about (3 to 5)/1



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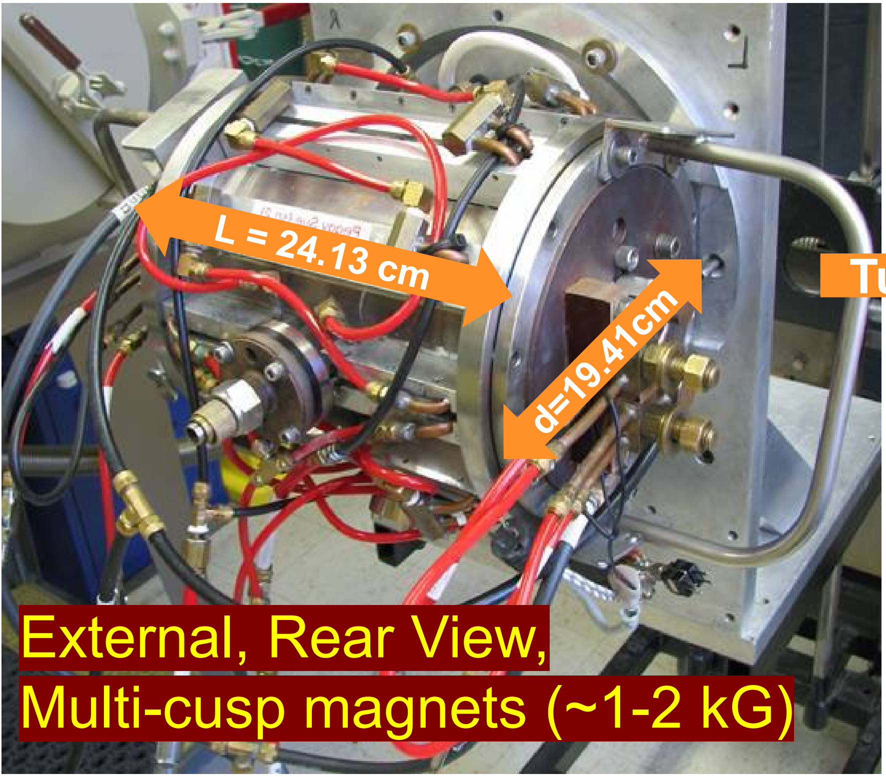
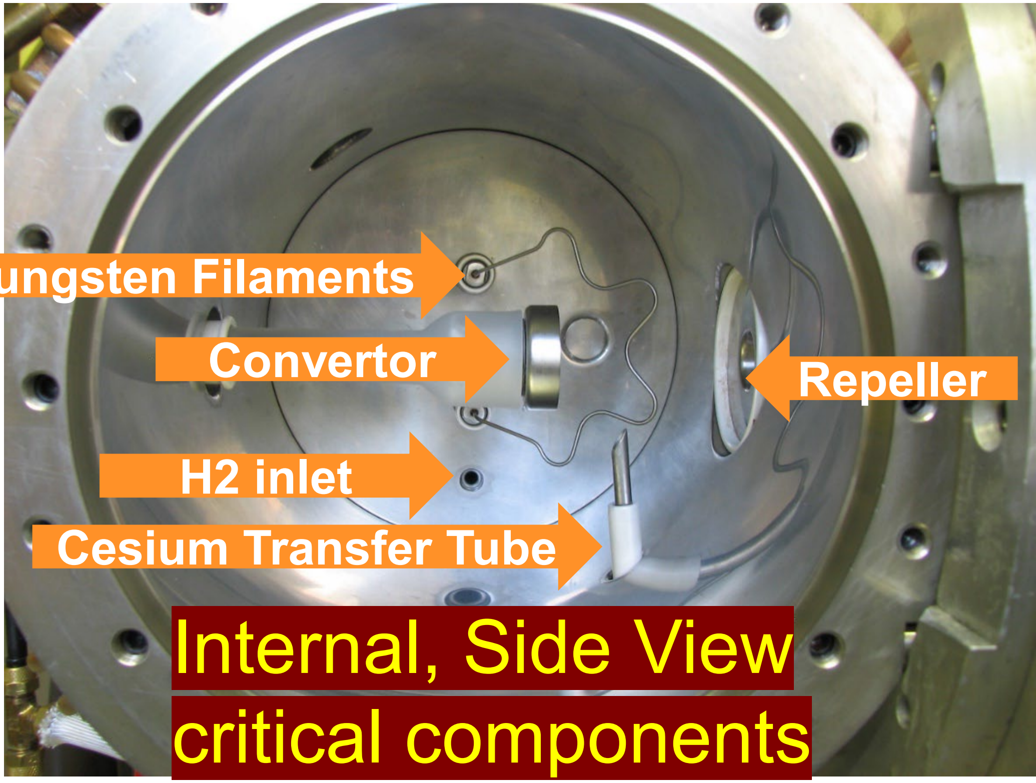
The LANSCE Multi-cusp Cesiated Surface-Conversion H- Source: Photos





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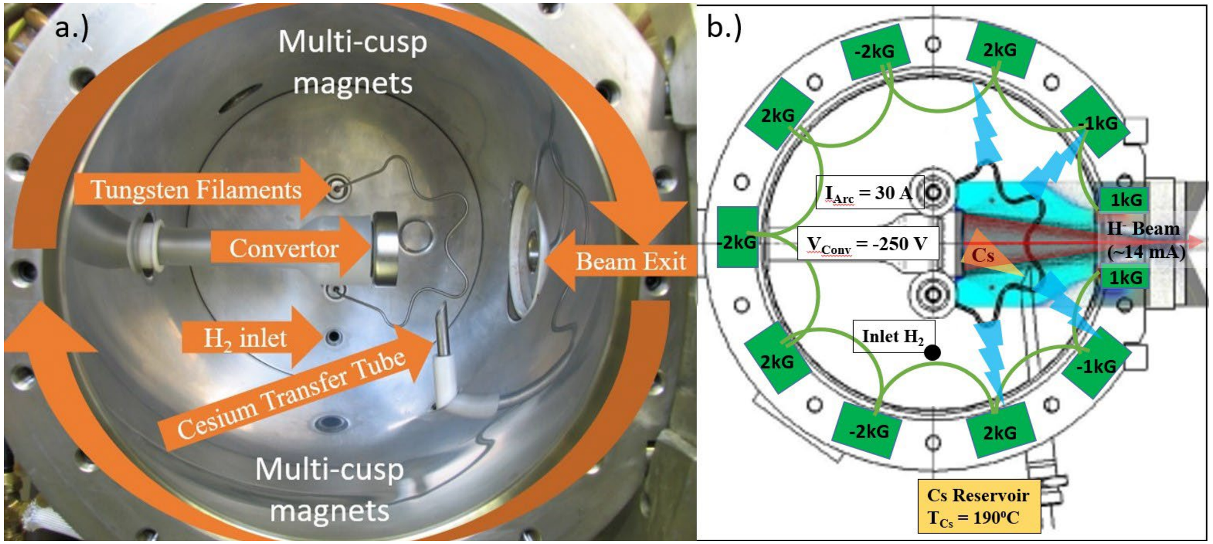
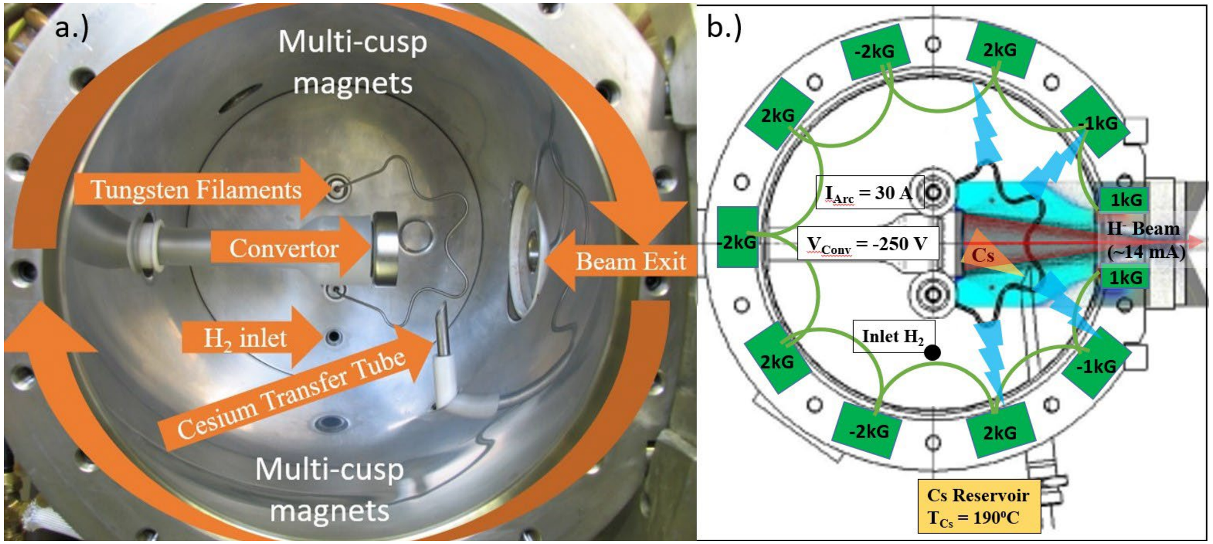
The LANSCE Multi-cusp Cesiated Surface-Conversion H- Source: How H- Ion beam is made



- Vacuum chamber filled with *Hydrogen gas* (~1.0 mTorr).
- *Tungsten filaments* that provide a pulsed electron arc current that ionizes this H_2 gas and creates a plasma
  - (Pulse: 120 Hz, 1 ms on, 7 ms off) (I_{DC} = 100 A, I_{arc} = ~30 A)
- Plasma confined by a decagonal *multi-cusp magnetic* field in the walls.
- H^+ ions in the generated plasma are attracted to a negatively biased *(-250 V) convertor.*
- The convertor is coated in cesium. Low work function of cesium encourages surface-conversion of H_0, H_x^+ to H^- ions.
- Negative Potential ejects produced H^- ions are promptly then ejected from the negative potential convertor, which is concavely shaped to focus the H^- ion beam towards the source exit and the high voltage beam injector (not shown).

The LANSCE Multi-cusp Cesiated Surface-Conversion H- Source: How H- Ion beam is made



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TLDR; Multi-Physics, Highly Dynamical Environment to Create H- Ions!

1.) LANSCE H- Ion source review

Motivation

- The internal process of Cs, H- inside the source is not well understood
- Dynamic processes 10-1000 μs scale

- Cesium surface-conversion is *the* vital ingredient for making H- beam
  - Side effects lead to beam instabilities, e.g. beam injector arc downs

- The H- beam creation, propagation, and neutralization inside the H- ion source is not understood.
  - How and where are H- Ions created and destroyed? How many?

Motivation

- The internal process of Cs, H- inside the source is not well understood
- Dynamic processes 10-1000 μs scale
  - **The correct tool is lasers tuned to atomic physics processes**
- Cesium surface-conversion is *thee* vital ingredient for making H- beam
  - Side effects lead to beam instabilities, e.g. beam injector arc downs
  - **Cs density: Optical absorption spectroscopy (D_2 transition, $S_{1/2} \rightarrow P_{3/2}$)**
- The H- beam creation, propagation, and neutralization inside the H- ion source is not understood.
  - How and where are H- Ions created and destroyed? How many?
  - **H- density: Measure photo-detachment of H- ions ($H^- + \gamma \rightarrow H^0 + e^-$)**

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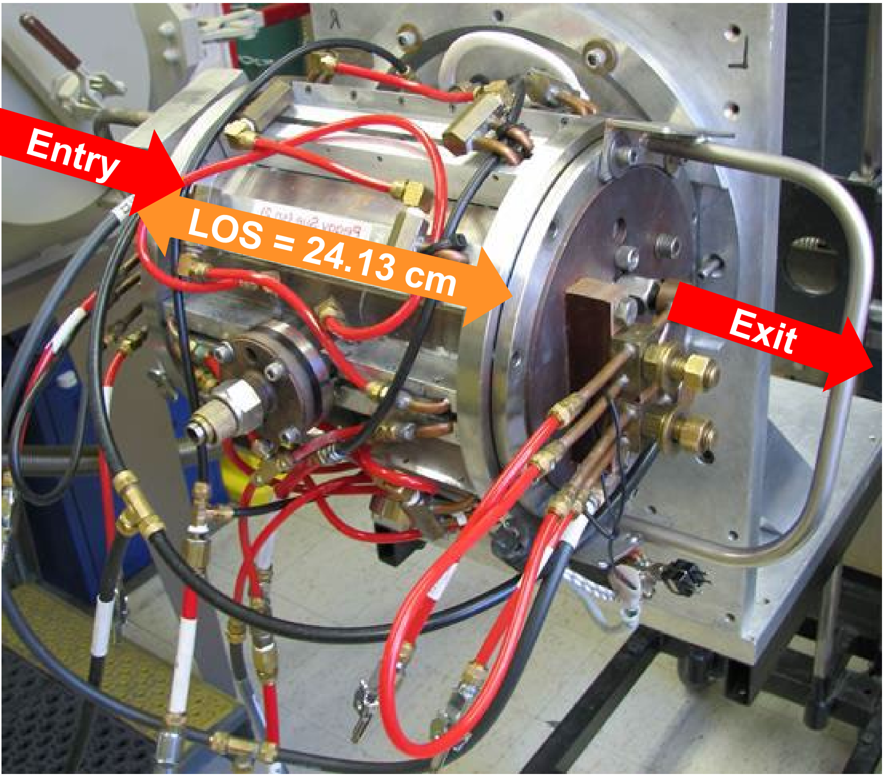
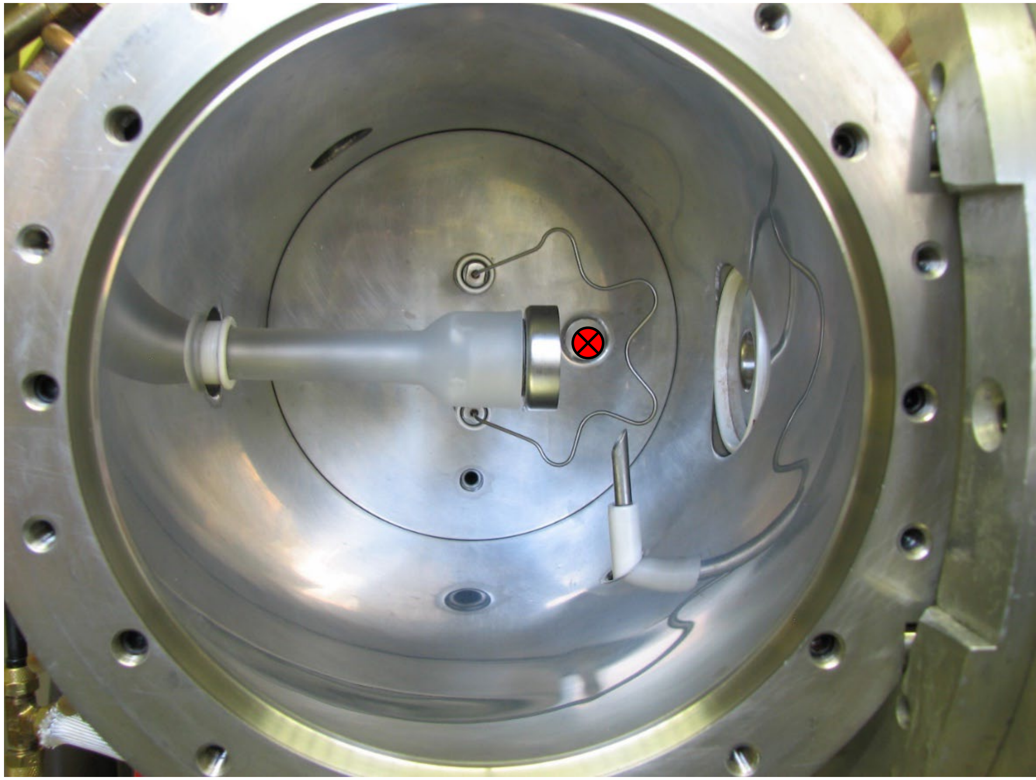
Future progress requires an "H- Ion Source Laser Diagnostic Stand"

Proposed laser diagnostic path





- Just misses filaments
- Off slightly off center from Cs port
- Center of Converter H- Beam Path

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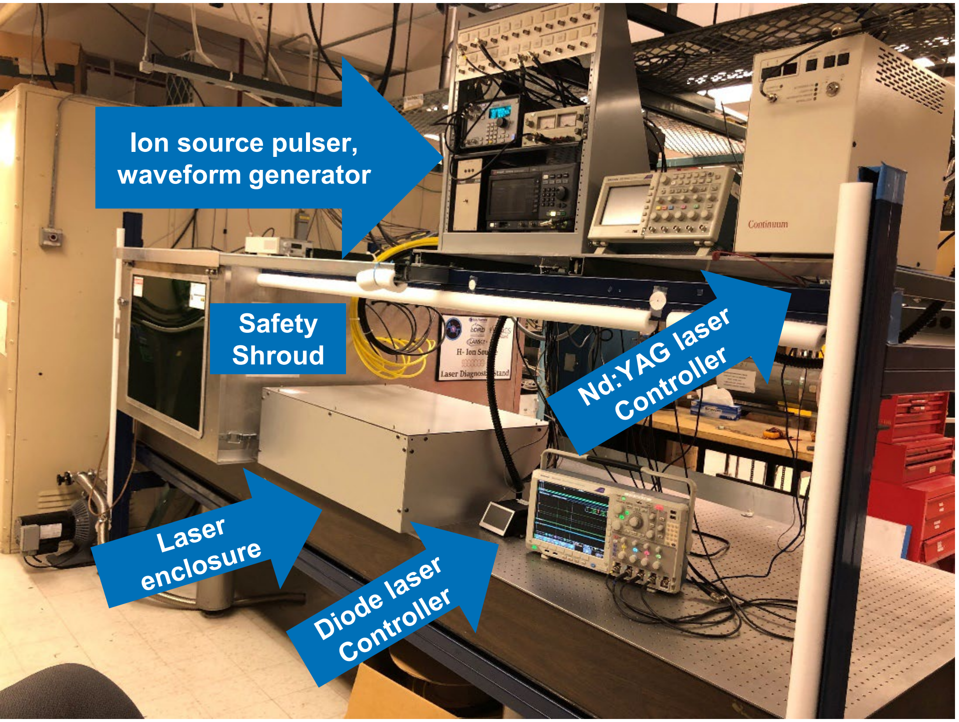
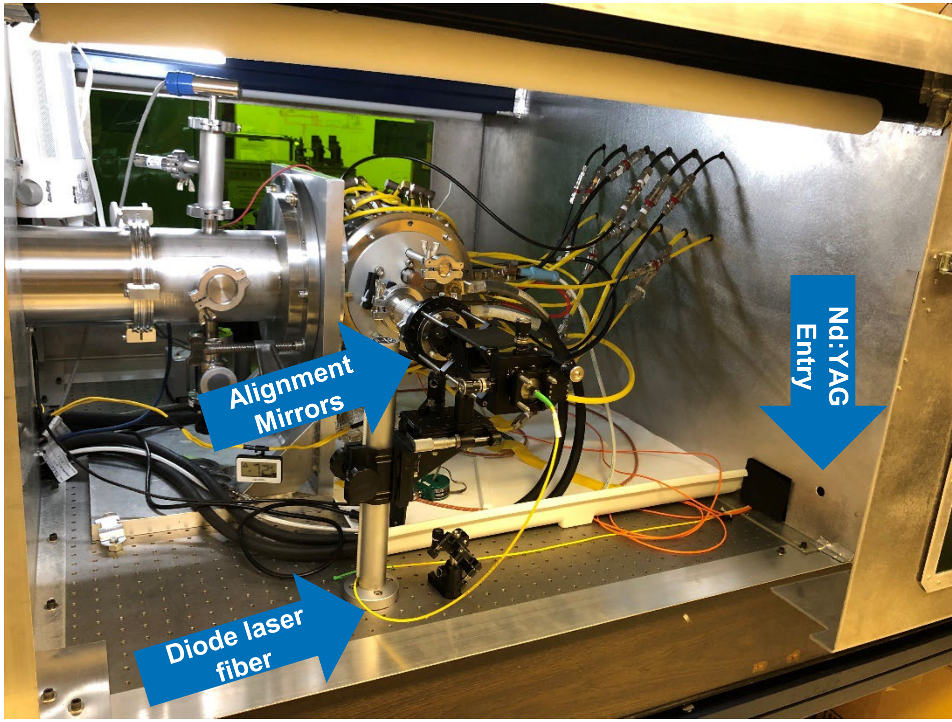
Pics of Laser Diagnostic Stand

West Side

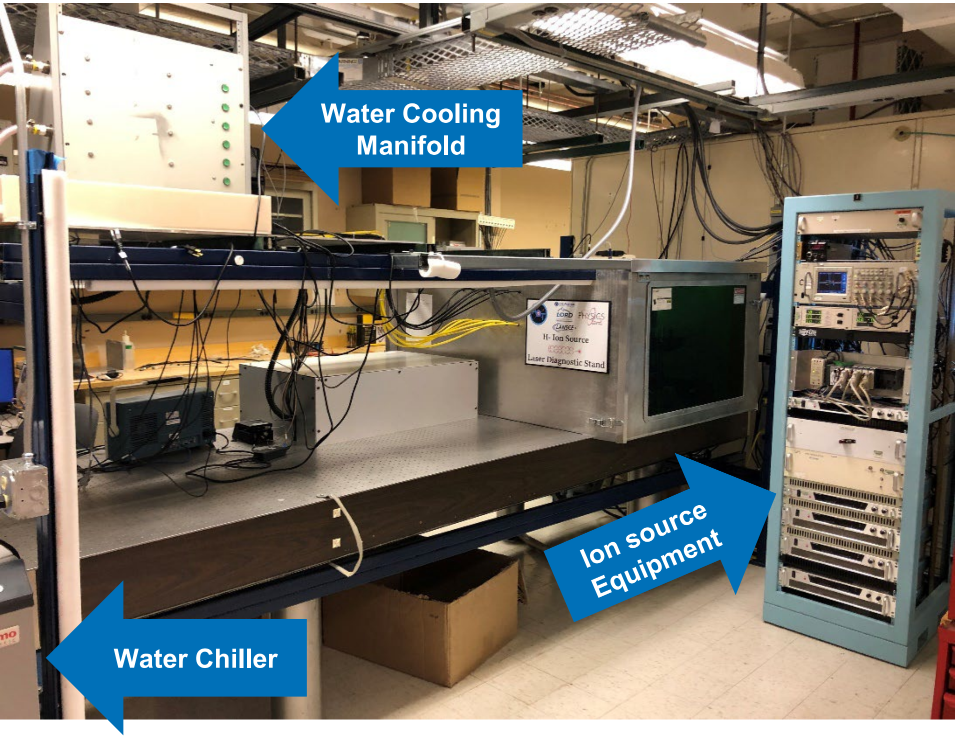


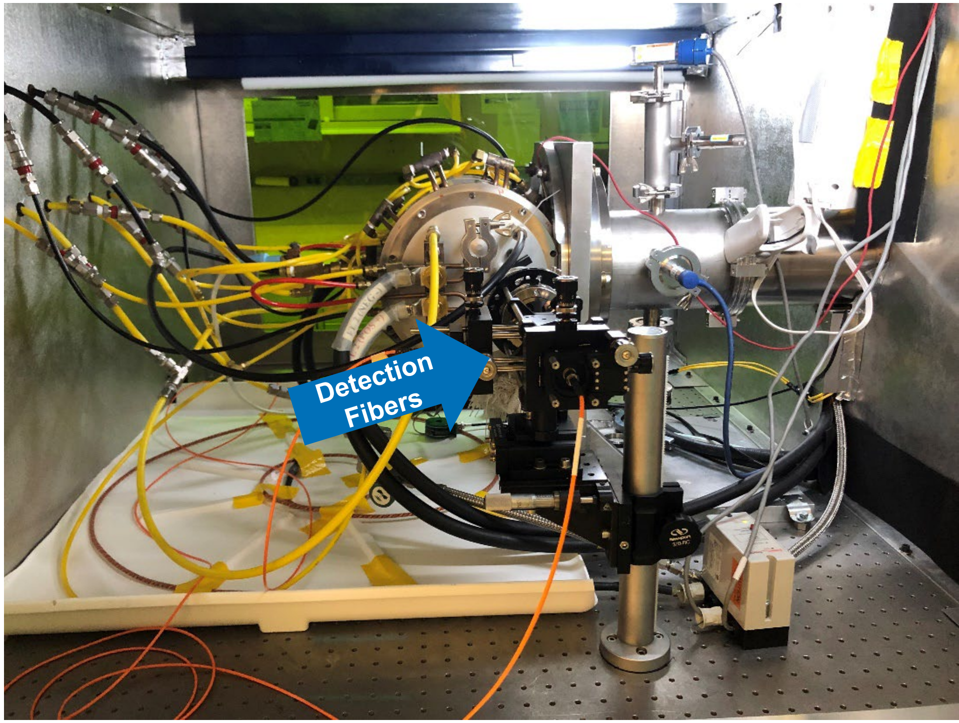


Diagnostic stand discussed at NIBS'2020
Fully built and functional!

Pics of Laser Diagnostic Stand

East Side





Diagnostic stand discussed at NIBS'2020
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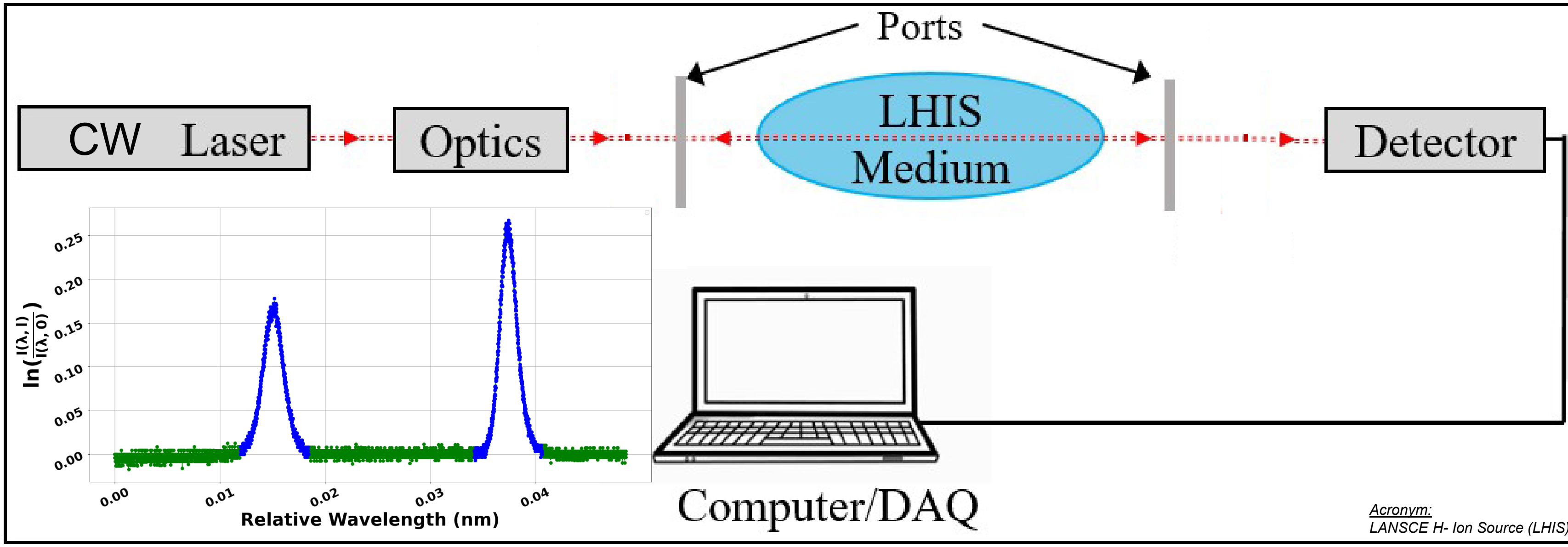
Cs Measurements using TDLAS

- Experimental setup
- The measurements
  - *Dynamic* Cs Density measurements during H- Ion Source Pulse
  - *Static* Cs Density measurements just before H- Ion Source Pulse
    - Change various source parameters
  - *Unstable* Cs Density measurements
    - Goes by many names: Cesiated Quench, Arc spike, Cesium burst
  - *Thermal* Cs measurements
    - 1^{st} Estimation of T_{Cs}

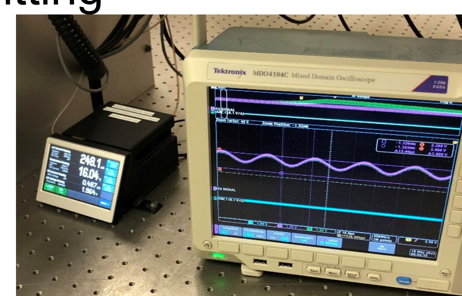
Optical setup block diagram. Resonant laser absorption for measuring Cesium Density



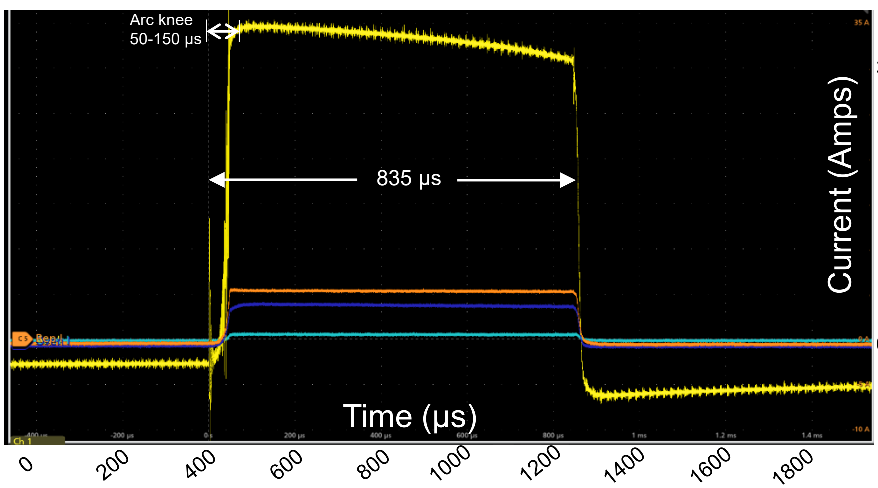
- A continuous, tunable diode laser is swept across an atomic transition (we use the D_2 transition, $6S_{1/2} \rightarrow 6P_{3/2}$, ~852 nm)
- Reference signal (not shown) is used for ln(λ,0) instead of fitting

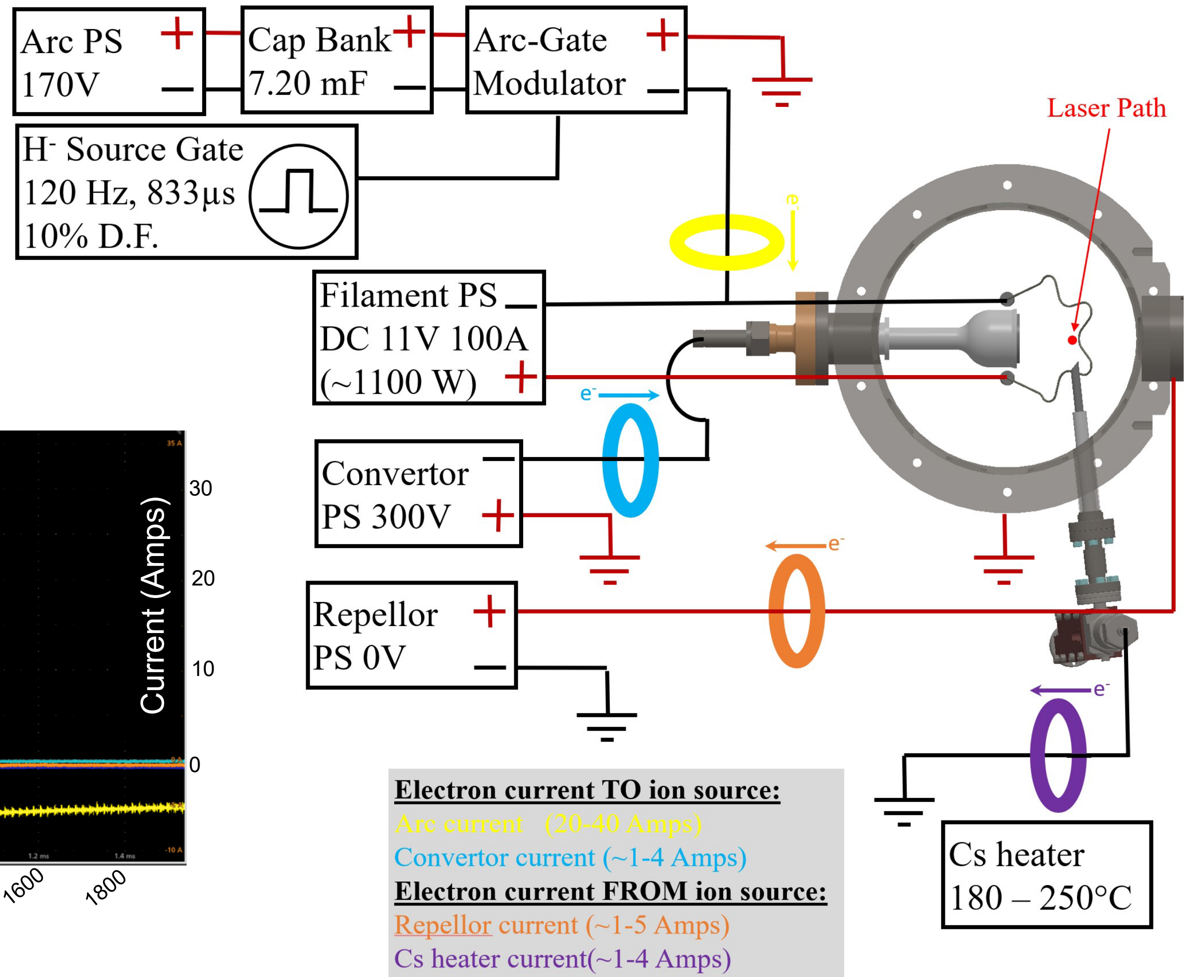
$$n_{Cs} = \frac{8\pi c}{\lambda_0^4}\frac{g_k}{g_i}\frac{1}{A_{ik} l}\int \ln\left(\frac{I(\lambda,l)}{I(\lambda,0)}\right) d\lambda$$

- Caveat: Depopulation effects not taken into account
  - Qualitative interpretation before quantitative



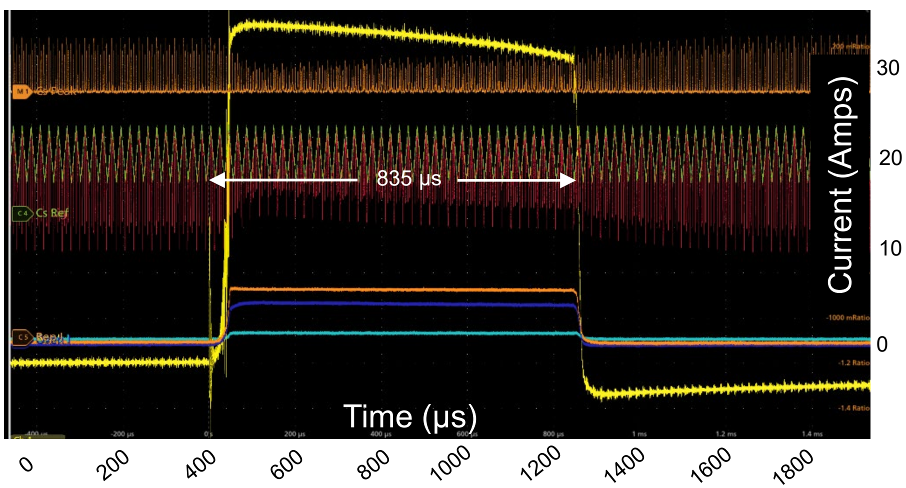
Relevant current measurements during ion source pulse





Relevant current measurements during ion source pulse With laser signal!

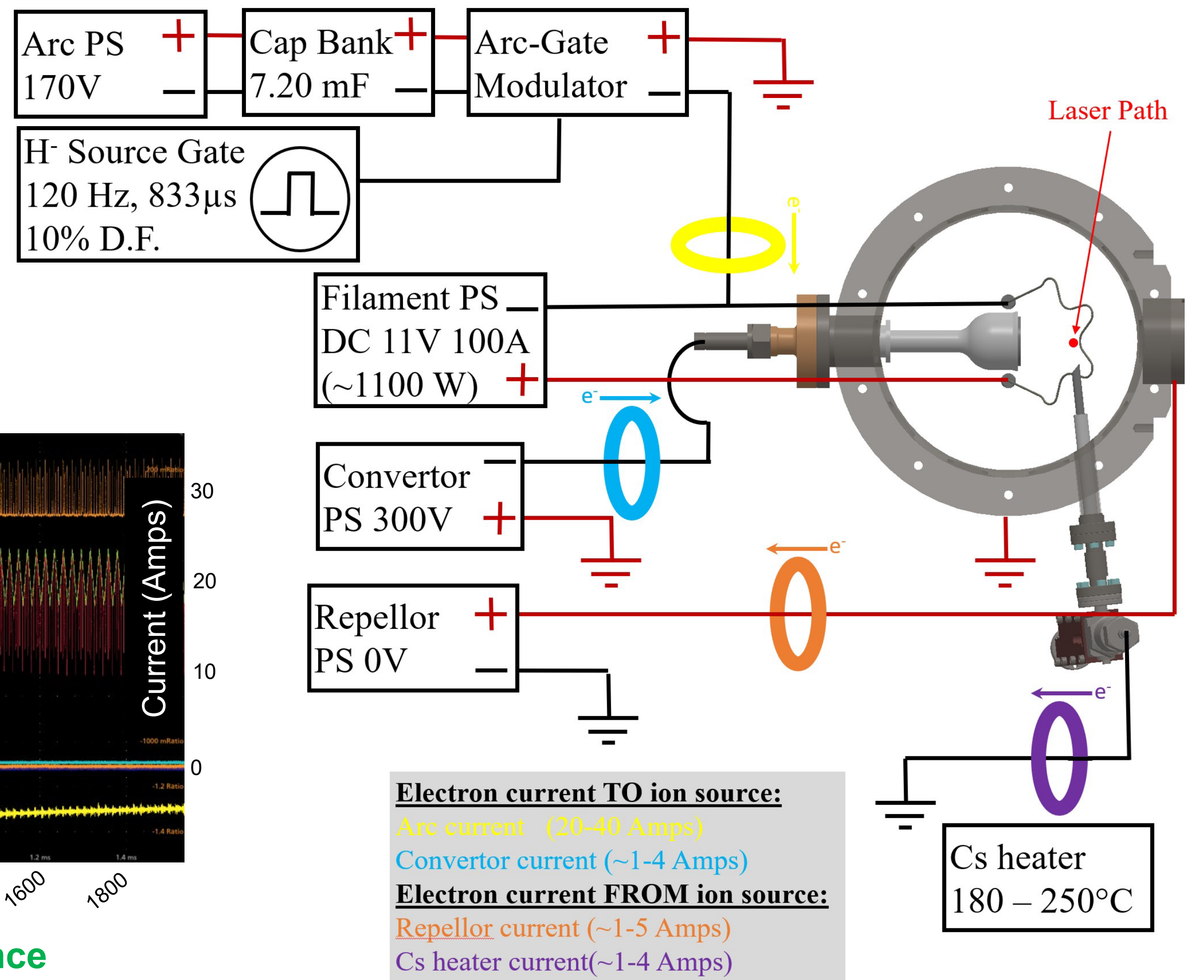
Apologies for the two "orange traces"!



Cs laser reference

Cs laser signal

-LN(Sig/Ref) (Upper Trace)



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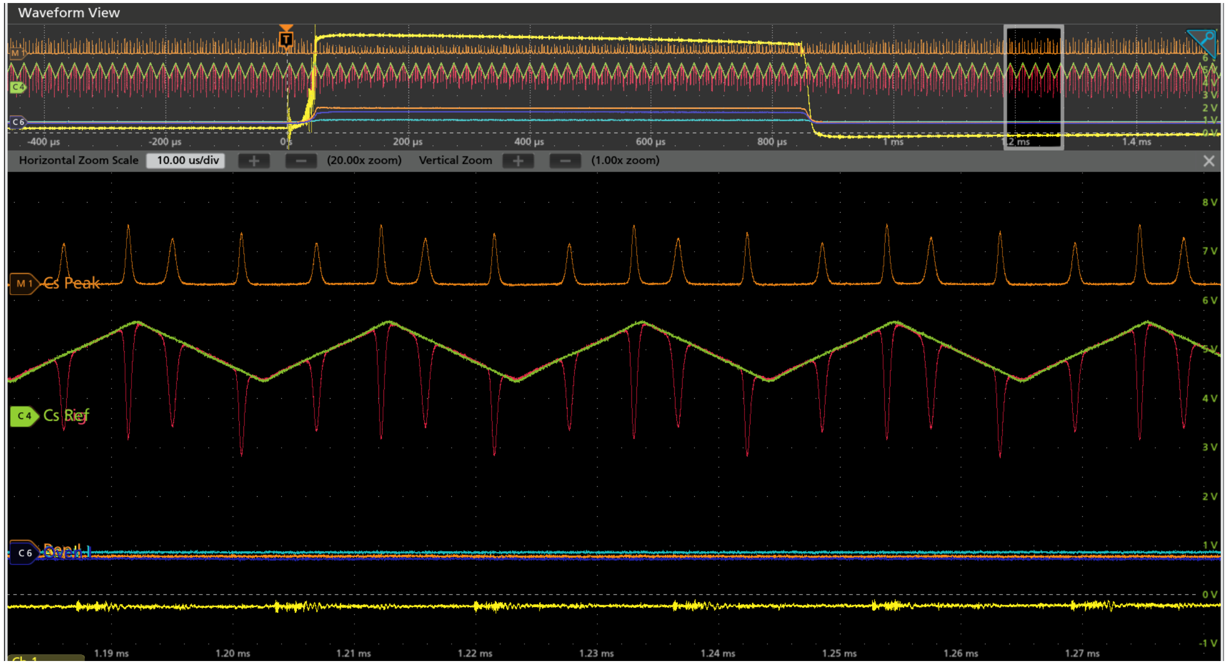
Zoom in: Cs Density outside source pulse



- Cs Reference
- Cs Signal
- -LN(Sig/Ref) (Upper Trace)

- Arc I
- Converter I
- Repeller I (Lower Trace)
- Cs Oven I

Zoom in: Cs Density outside source pulse

Cs peaks shorten and broaden inside the pulse compared to outside

- Cs Reference
- Cs Signal
- -LN(Sig/Ref) (Upper Trace)

- Arc I
- Converter I
- Repeller I (Lower Trace)
- Cs Oven I

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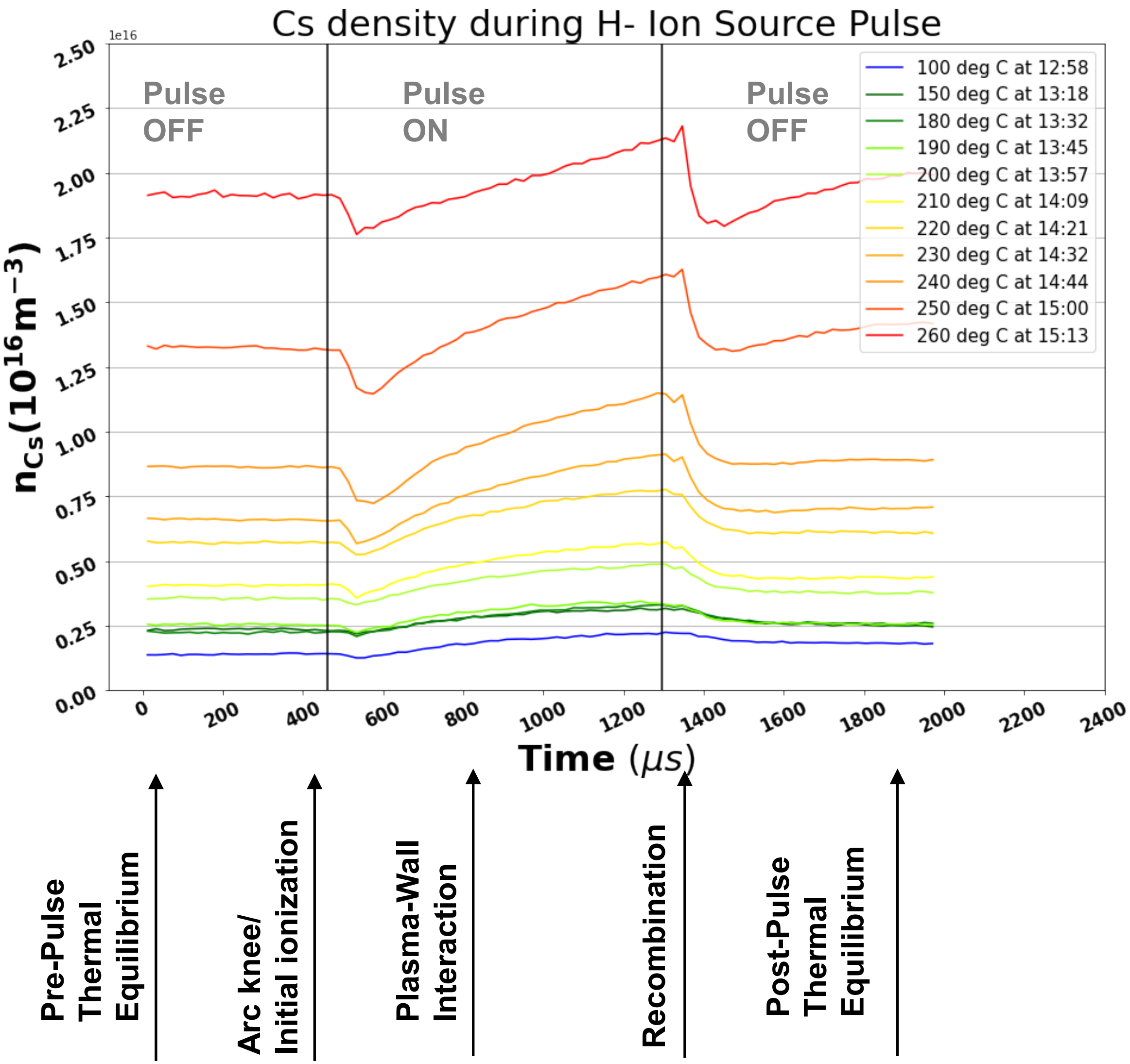
Cs Density during an H- Beam Pulse



- Ion Source Fully running
- Adjust Cs Oven Temperature from 100°C to 260 °C
- Rate of Change in density as expected from Cs vs vapor pressure at ~1 mTorr.

- Cs during initial transfer is 250°C
- Nominal running ~180°C

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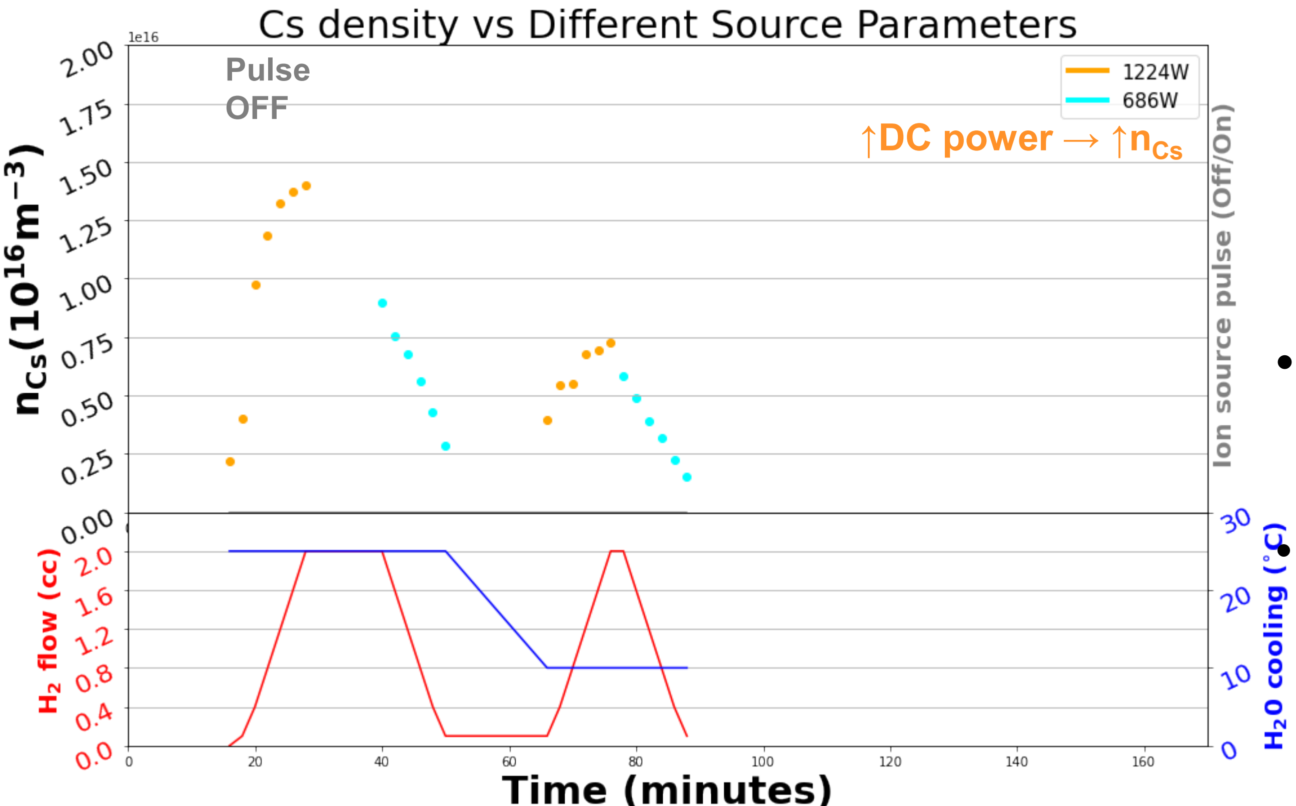
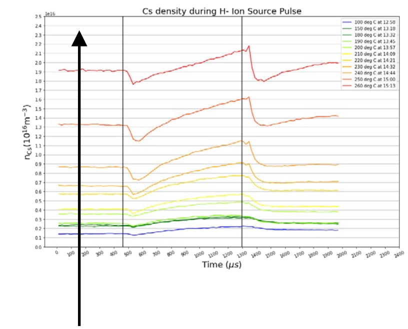
Pre-Pulse Thermal Equilibrium Cs Density vs different Source Parameters



↑ H_2 flow → ↑ n_{Cs}

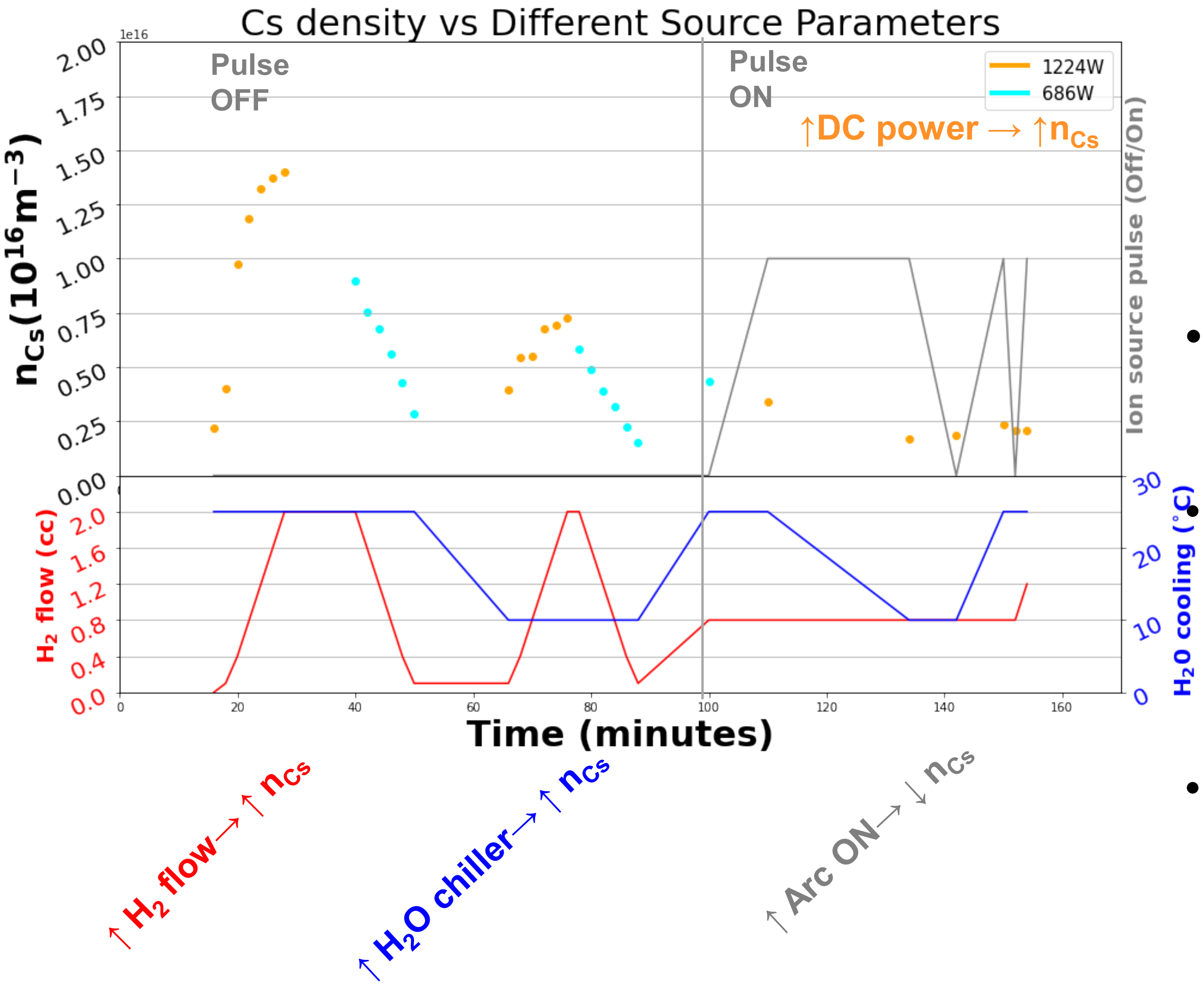
↑ H_2O chiller → ↑ n_{Cs}

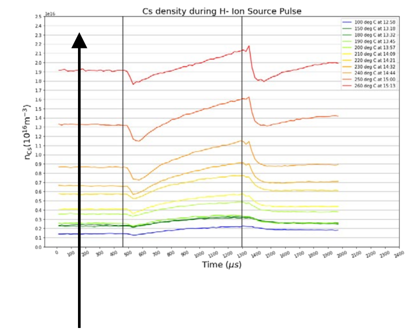
↑ Arc ON → ↓ n_{Cs}



- Cs Oven Temp OFF
  - Relying on Cs already in the chamber
- Pulse OFF (Static)
  - Direct relationship to n_{Cs}
    - Filament Power
    - H_2 flow
    - H_20 chiller

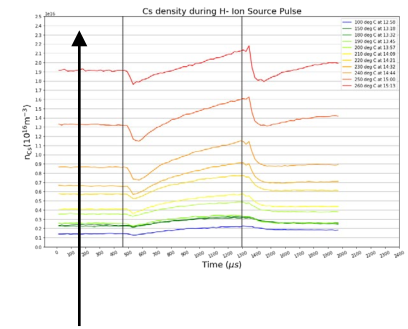
Pre-Pulse Thermal Equilibrium Cs Density vs different Source Parameters

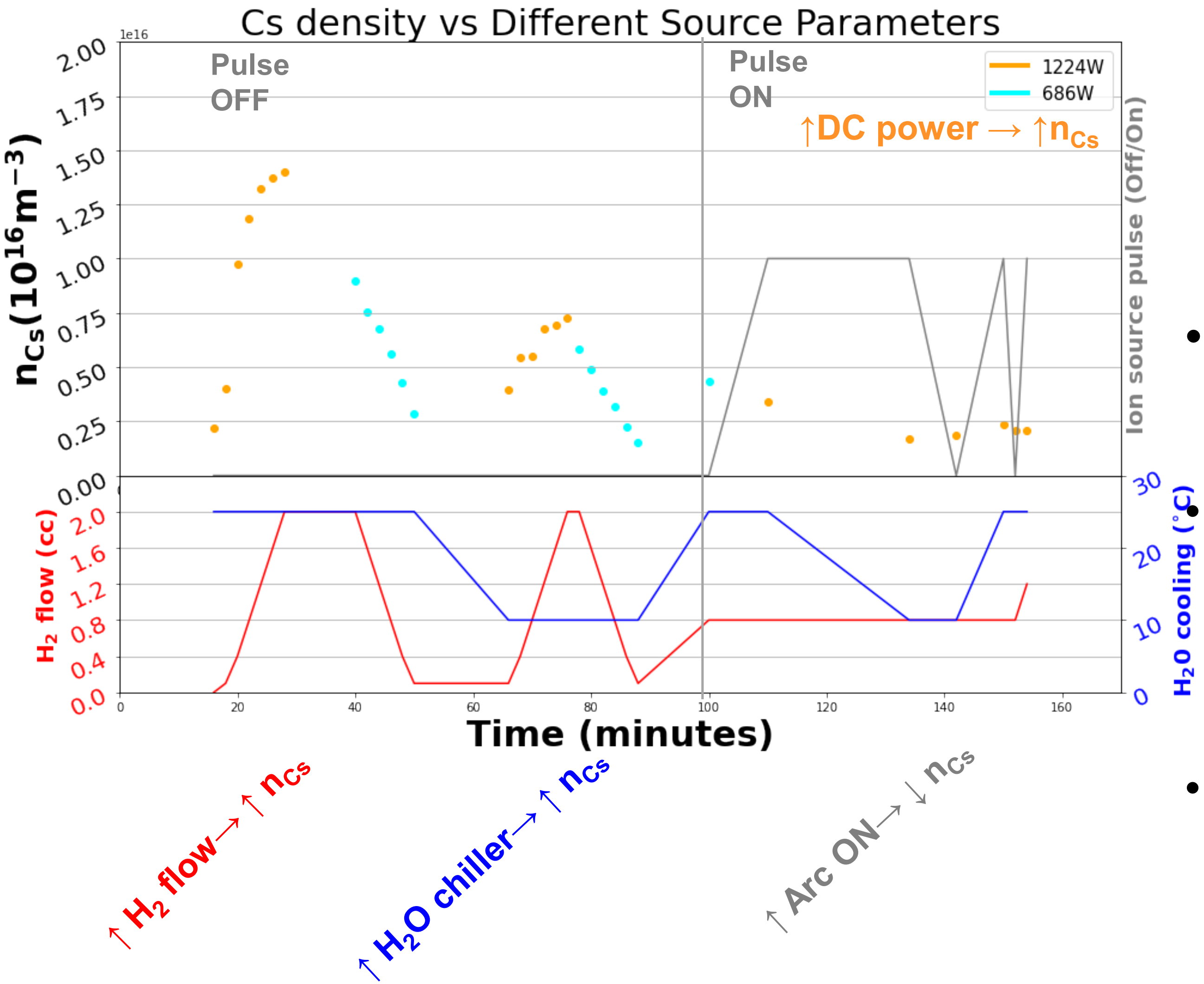




- Cs Oven Temp OFF
  - Relying on Cs already in the chamber
- Pulse OFF (Static)
  - Direct relationship to n_{Cs}
    - Filament Power
    - H_2 flow
    - H_20 chiller
- Pulse ON (Dynamic)
  - Inverse relationship to n_{Cs}
  - Suppression of n_{Cs} in LOS
  - Other effects less pronounced

Pre-Pulse Thermal Equilibrium Cs Density vs different Source Parameters



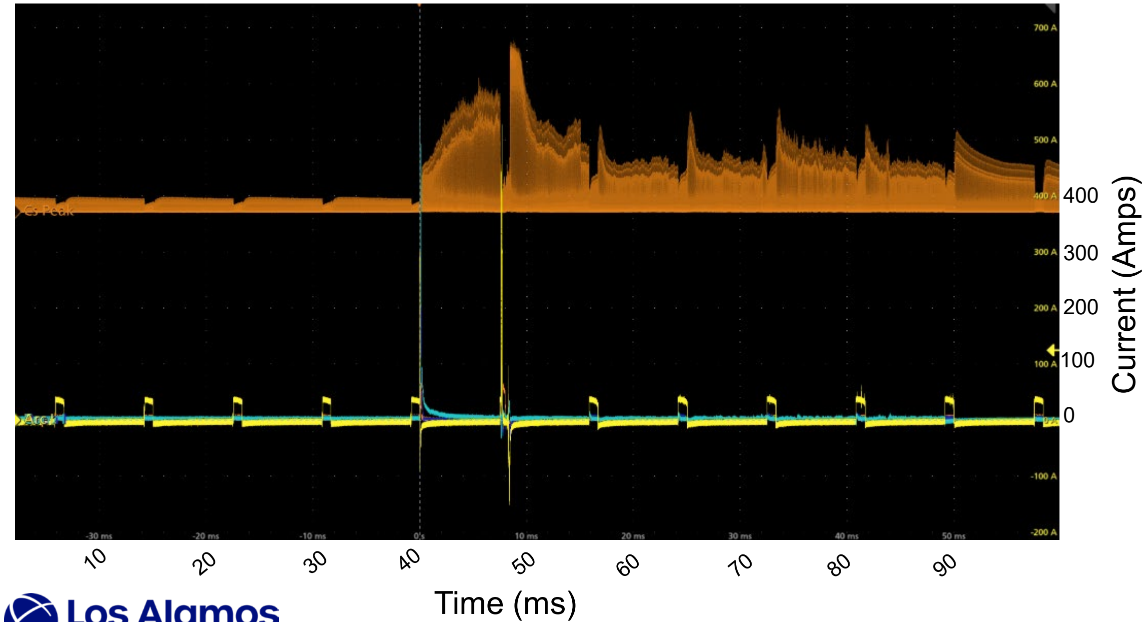


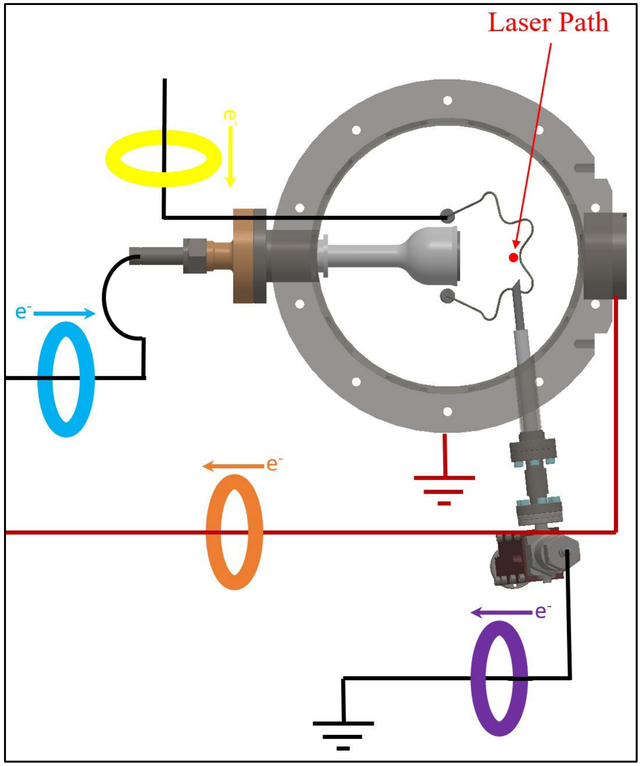
- Cs Oven Temp OFF
  - Relying on Cs already in the chamber
- Pulse OFF (Static)
  - Direct relationship to n_{Cs}
    - Filament Power
    - H_2 flow
    - H_20 chiller
- Pulse ON (Dynamic)
  - Inverse relationship to n_{Cs}
  - Suppression of n_{Cs} in LOS
  - Other effects less pronounced

Continual Cs evaporation required to overcome this suppression

Ion source Cesiated Quench and Spike studies

- Random cesiation effect cause instabilities on the Arc and/or Converter current in the Ion source.
  - Large → Arc/Converter Quench
  - Small → Arc/Converter Spike
- Cs laser perfect for studying this phenomena.
- At LANSCE, these cause beam instabilities
  - Arc down H- Ion Source 80 kV injector (1-5 per hour)
- *What follows: many qualitative plots of one of these events (Below)*

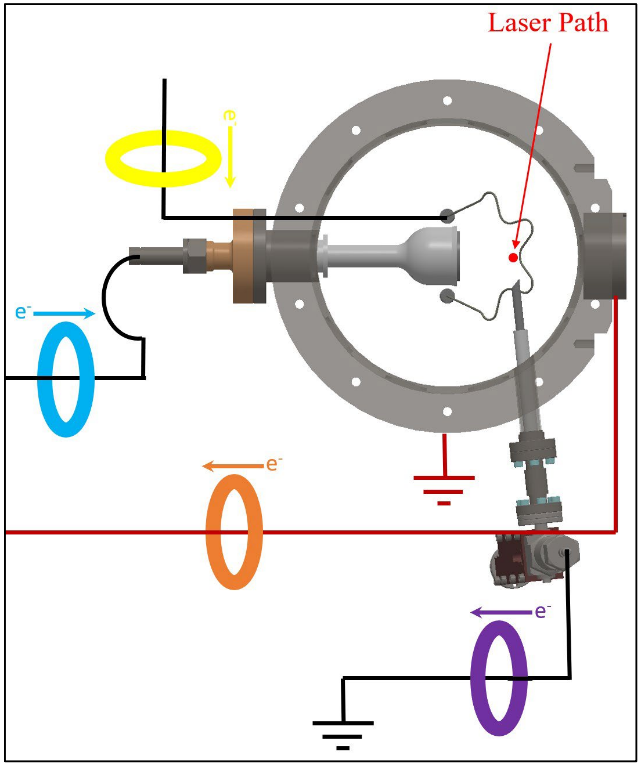


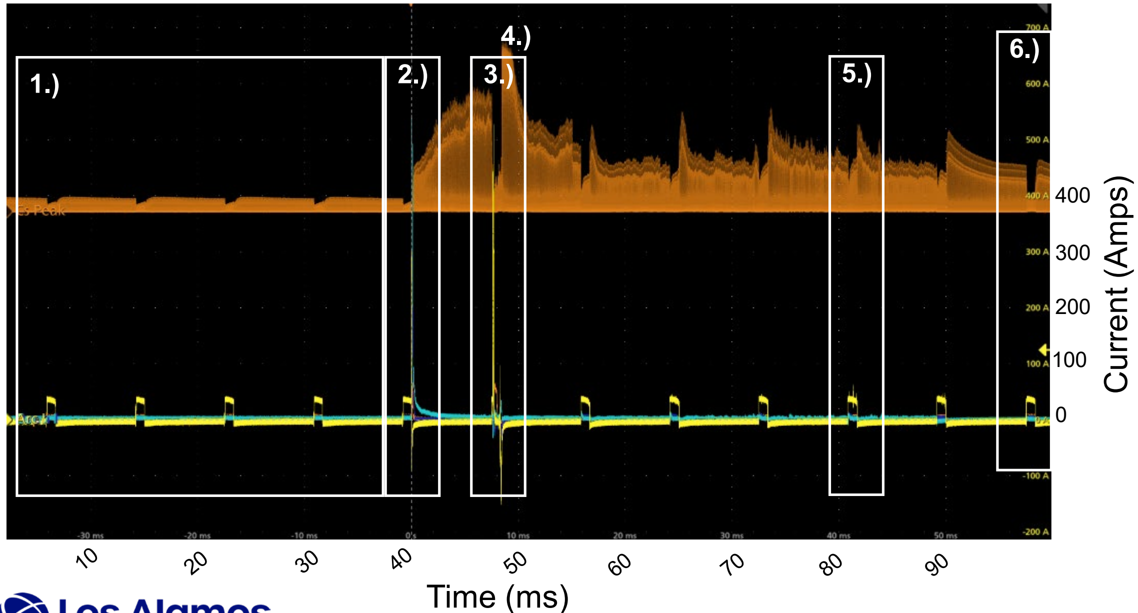


-LN(Sig/Ref) (upper trace)
Arc I
Converter I
Repeller I (lower trace)
Cs Oven I

Ion source Cesiated Quench and Spike studies

- 1.) Nominal pulses
- 2.) 1st Cesiated Quench
- 3.) 2nd Cesiated Quench
- 4.) Line Saturation
- 5.) Arc Spikes
- 6.) Slow return to nominal?

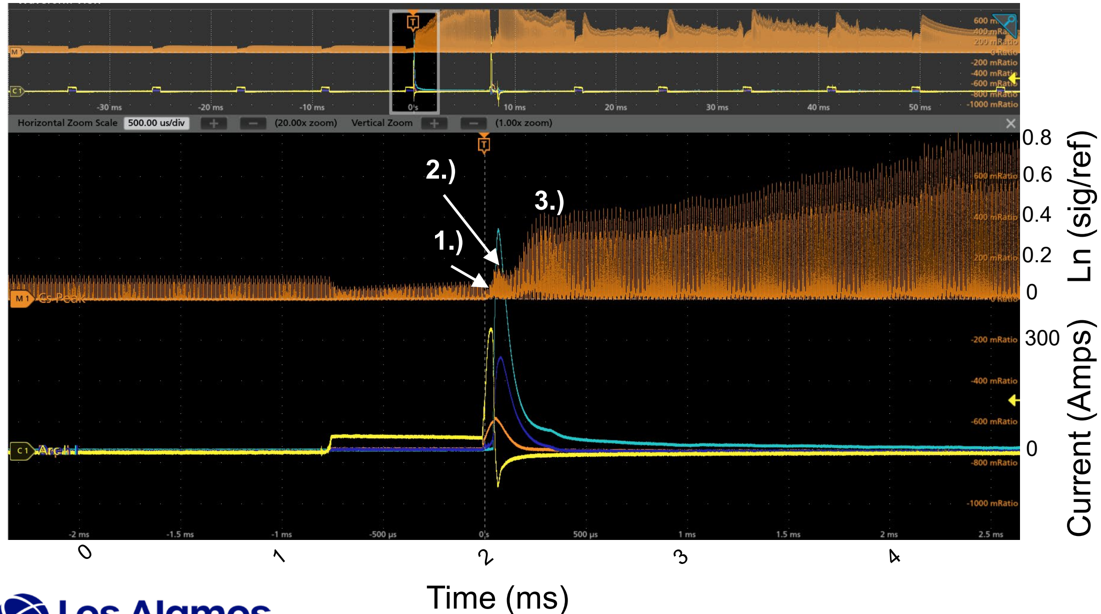


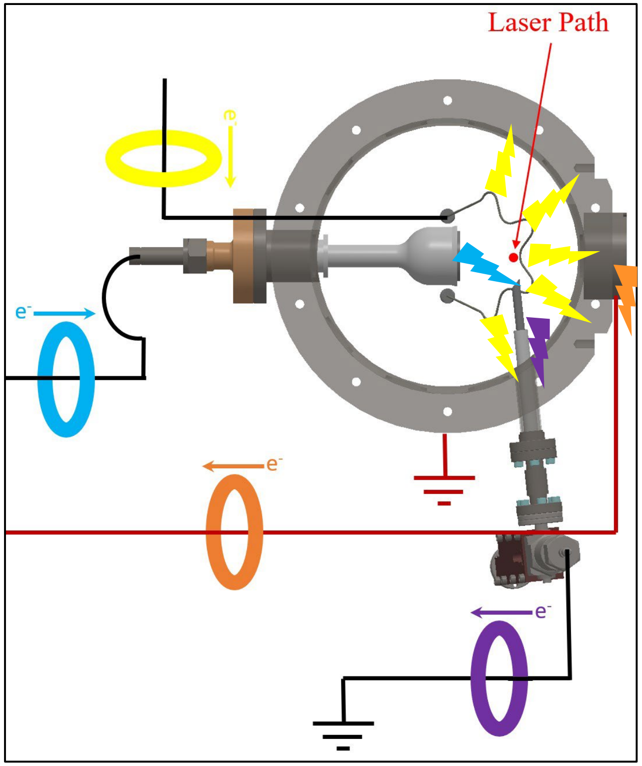


-LN(Sig/Ref) (upper trace)
Arc I
Converter I
Repeller I (lower trace)
Cs Oven I

1st Cesiated Quench

- Arc current appears to shorted, goes everywhere
  - Partially to the Repeller
- Converter then Arcs to Cs Oven
- 1.) Brief decrease onset of Arc Current
- 2.) Brief increase onset of Converter Current
- 3.) Cs everywhere after pulse off!

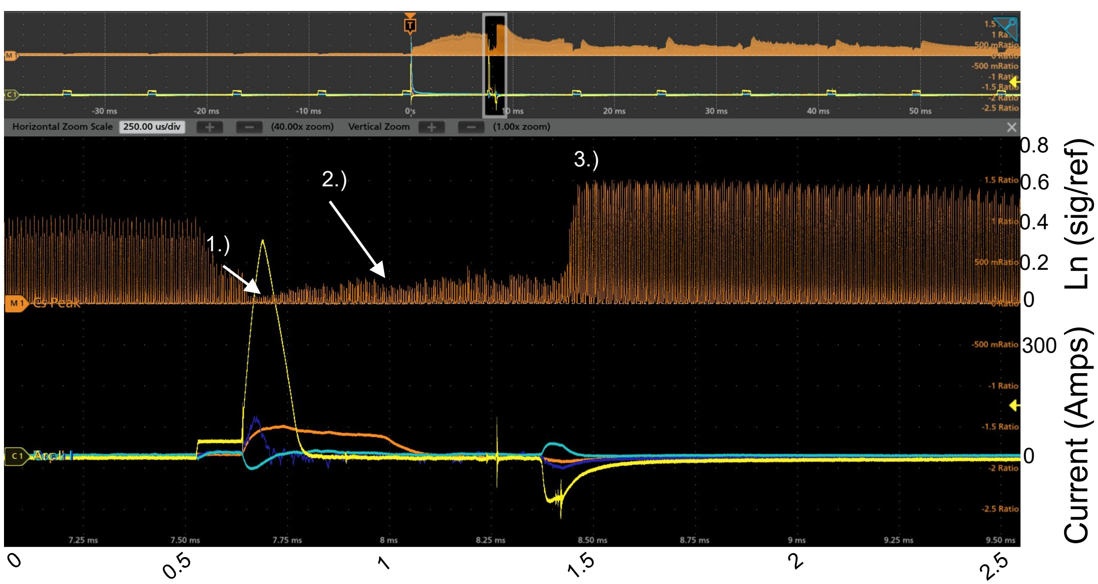


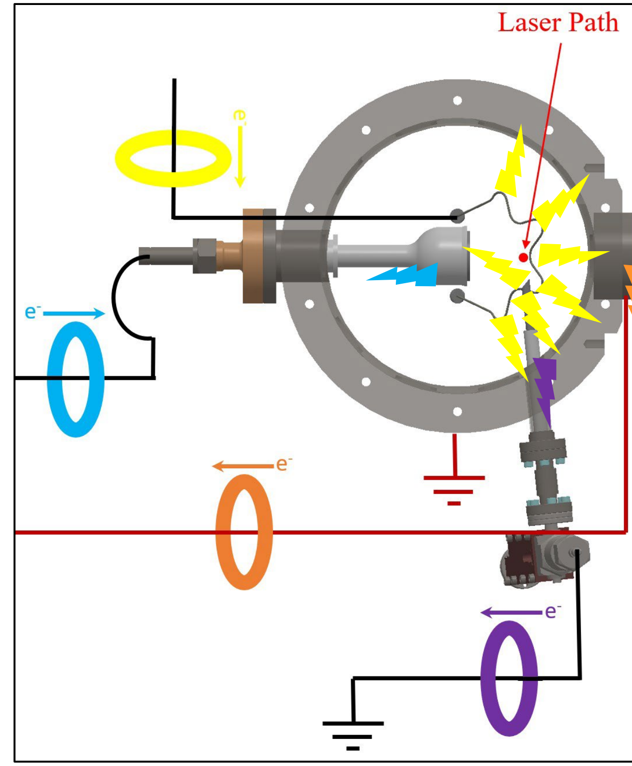


-LN(Sig/Ref) (upper trace)
Arc I
Converter I
Repeller I (lower trace)
Cs Oven I

2nd Cesiated Quench

- Arc current appears to shorted, goes everywhere
  - Partially to the Repeller
  - Partially to the Cs Oven
  - Partially to the Converter
- 1.) Brief decrease onset of Arc Current
- 2.) Plasma-Wall interactions
- 3.) Cs everywhere after pulse off!





-LN(Sig/Ref) (upper trace)
Arc I
Converter I
Repeller I (lower trace)
Cs Oven I

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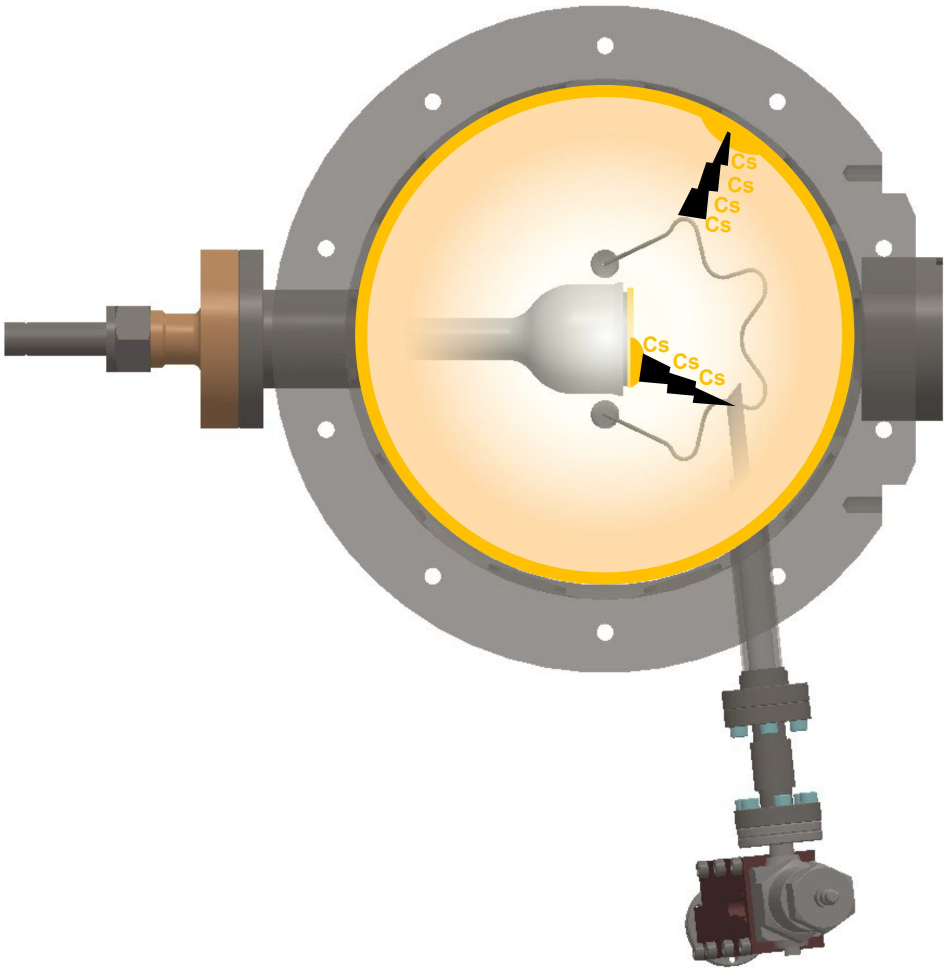
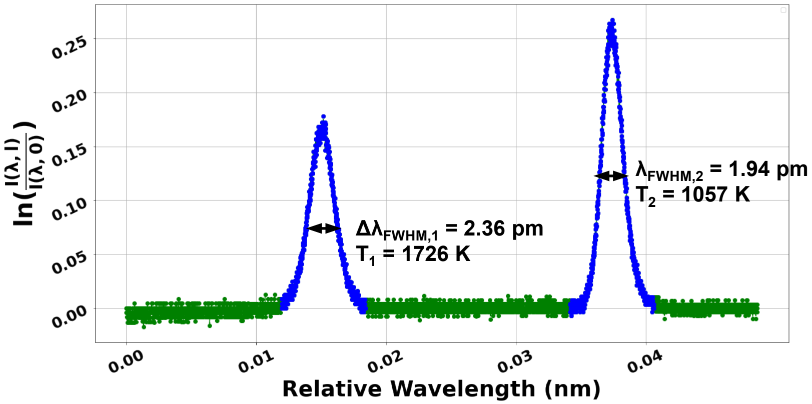
What causes these Cesiated quenches?

- Nonuniform **Cs deposits** that build up on walls/converter?
- Nonuniform Evaporative effects?
  - Creates conductive plasma?
- **Path to Ground** Created somehow
  - Non-neutral plasma?
  - Instantaneous “paschen follies”?
- More Quenches seen when turning on cold source
  - Non-uniform Cold Cs deposits



First look at Cs Temperature during an H- Beam Pulse

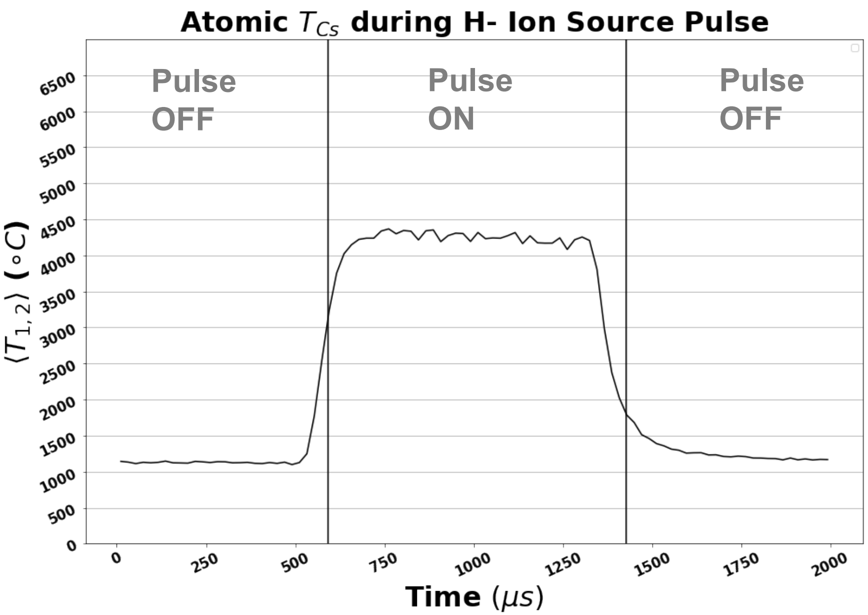


$$\Delta\lambda_d(T_{\mathrm{Cs}}) = 2\frac{\lambda_0}{c}\sqrt{\frac{2\ln(2)\mathrm{k_B}T_{\mathrm{Cs}}}{m}}$$

$$T_1(\Delta\lambda_{\mathrm{FWHM,1}}) = -300 + 29\cdot\Delta\lambda_{\mathrm{FWHM,1}}/\mathrm{pm} + 350\cdot(\Delta\lambda_{\mathrm{FWHM,1}}/\mathrm{pm})^2,$$

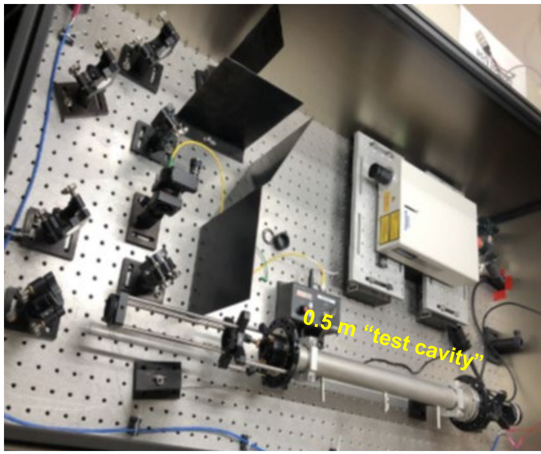
$$T_2(\Delta\lambda_{\mathrm{FWHM,2}}) = -300 + 1.7\cdot\Delta\lambda_{\mathrm{FWHM,2}}/\mathrm{pm} + 360\cdot(\Delta\lambda_{\mathrm{FWHM,2}}/\mathrm{pm})^2.$$

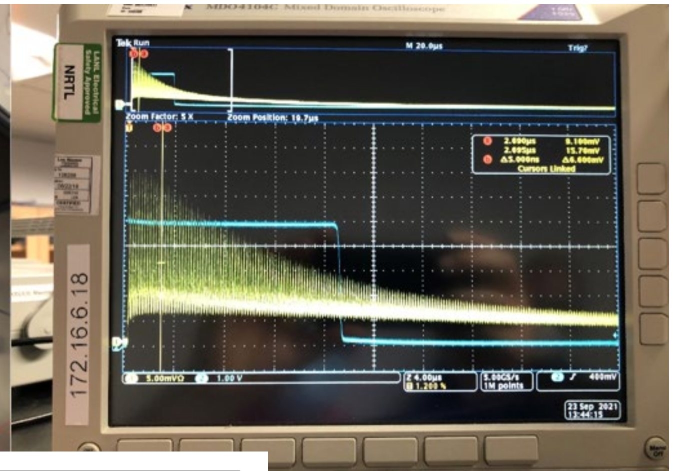
M. Lindaur, Master Thesis, Univ. Augsburg (2017)

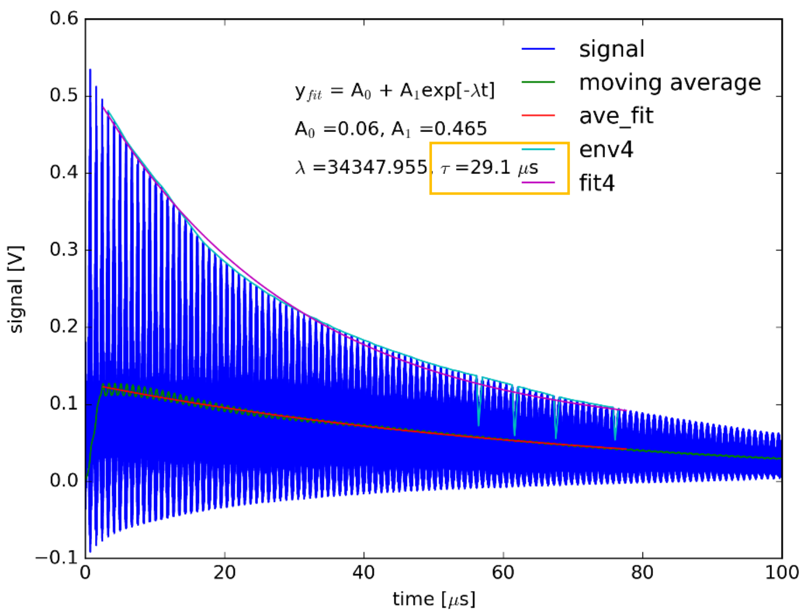


- **Pulse OFF** temp (~1200°C) is similar to the in-house *emissivity* measurements of filament DC temperature (~1700°C)
- Work ongoing to determine to proper accuracy

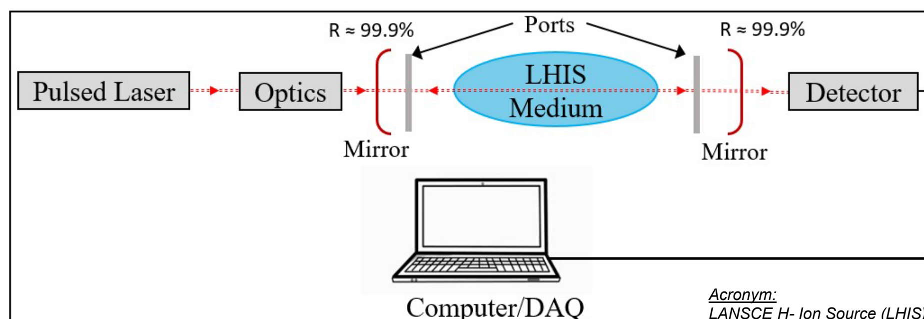
H- Density Measurements using CRDS
Test cavity



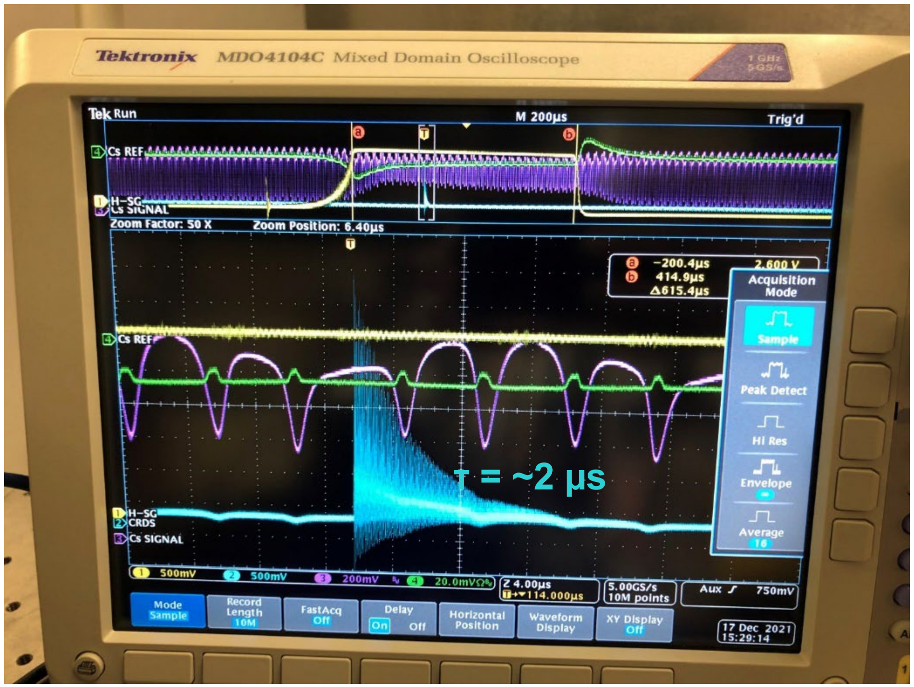


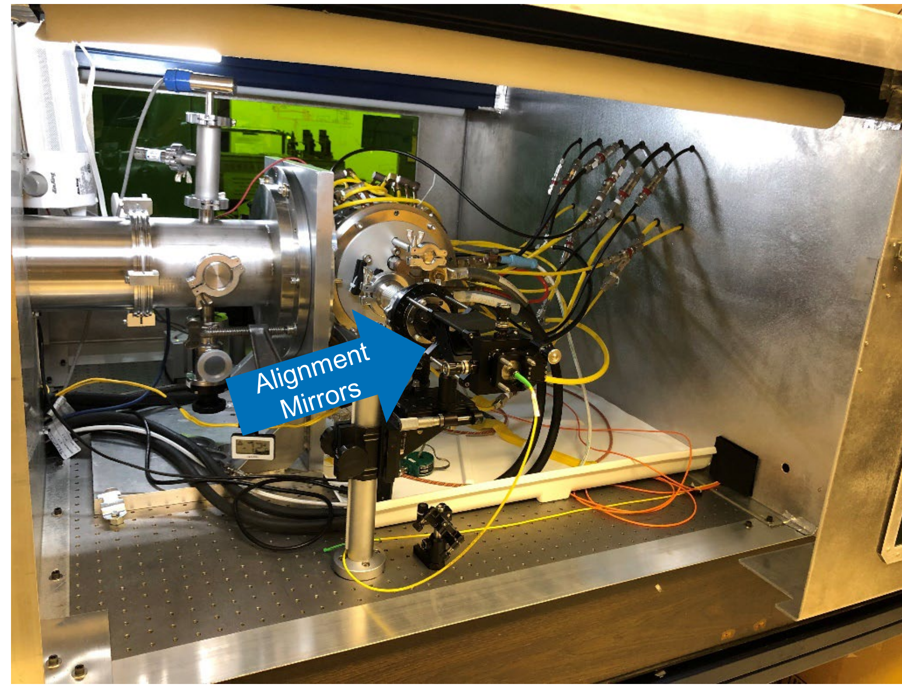


- 29 μs during test. (~0.5 m cavity length)
- Achieved good characterization of CRDS



H- Density Measurements using CRDS
H- Ion Source





- Decay only 2 µs, vs 26 µs during test. (~0.8 m cavity length)
- Issue: Need to Improve alignment mirror manifold
  - Atmosphere vs vacuum alignment. Slight skew between east/west optical ports.
- Issue: Decay became shorter over time
  - Mechanical vibration/thermal issues?
  - Mirror contamination

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Conclusions

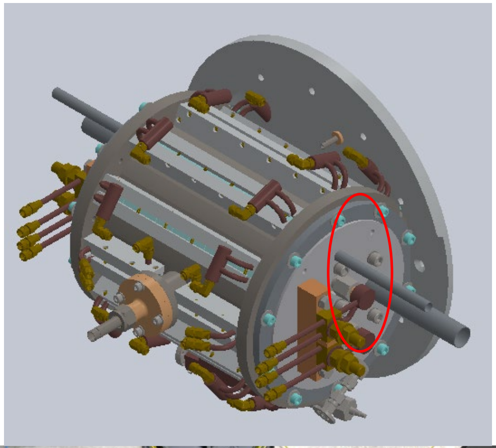
- Fully developed H- Ion Source Laser Diagnostic Stand
  - 1^{st} results of Cs TDLAS measurements shown
  - Stay tuned for H- measurements

Acknowledgements

- We are grateful to collaborators at the Max Planck Institute for Plasma Physics –Garching
  - Ursel Fantz, the ITED division leader at IPP Garching
  - Bernd Heinemann, NBI group leader
  - Dirk Wünderlich, experimental leader of the ELISE test facility
  - *Special Thanks*
    - Christian Wimmer, experimental leader at BATMAN Upgrade test facility
    - Alessandro Mimo, CRDS, TDLAS expert at BATMAN and ELISE
- We are grateful to our funding agencies:
  - LANL LDRD Office
  - The Department of Energy, and the National Nuclear Security Administration for supporting our work.

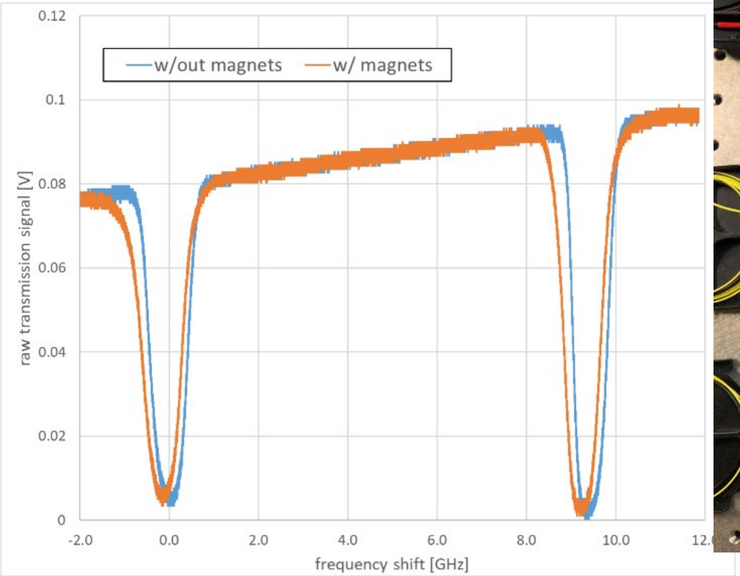
Backup

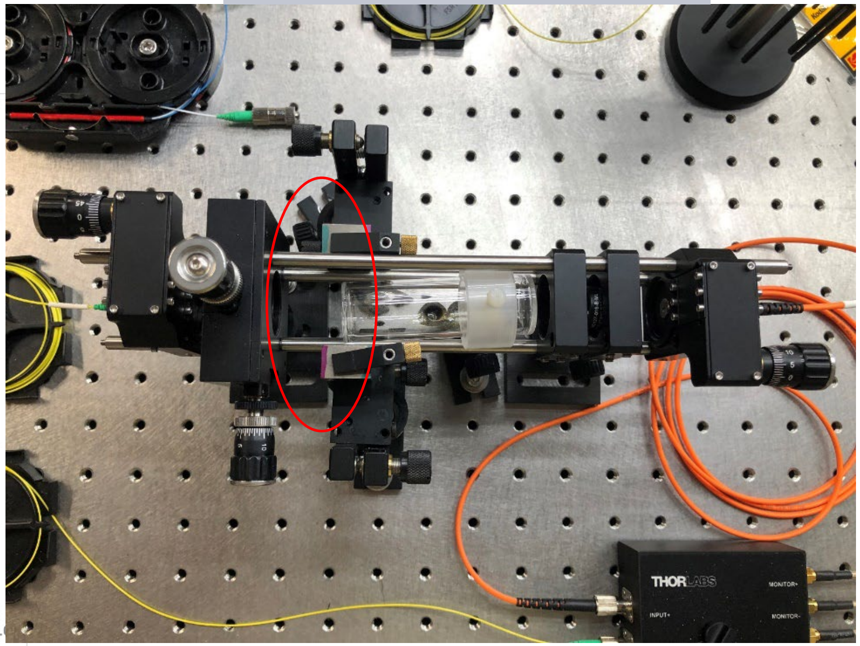
Checking for Magnetic Effects



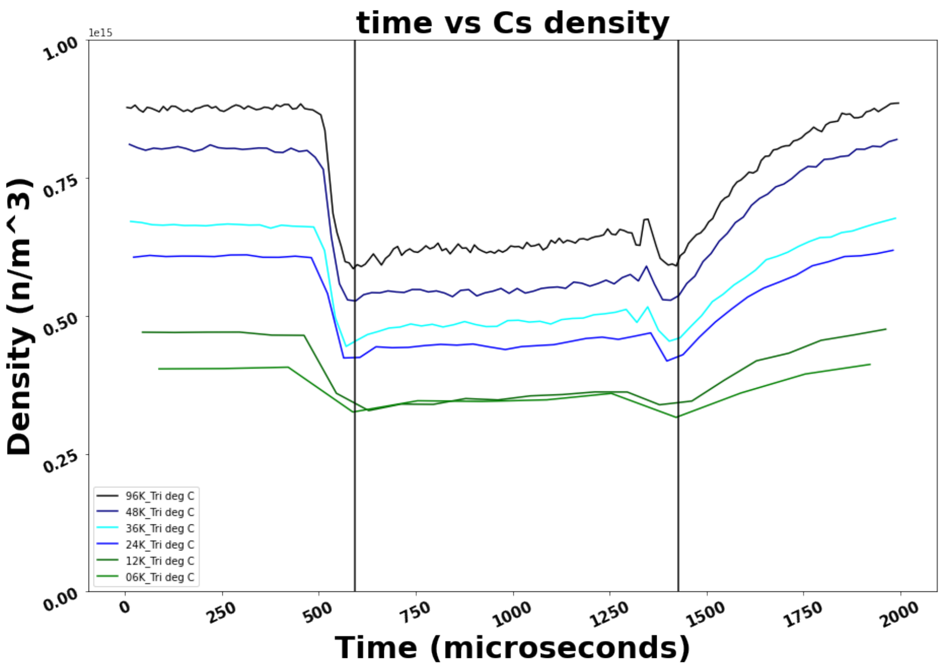
- Magnetic field strongest by the walls.
- Will magnetic field at entry/exit cause Zeeman splitting?
- The effect is negligible/manageable
  - 2kG magnets tested in lab
  - 1kG in source
- No mag: 5.61×10^{16} atoms/m^3
- With mag: 5.94×10^{16} atoms/m^3

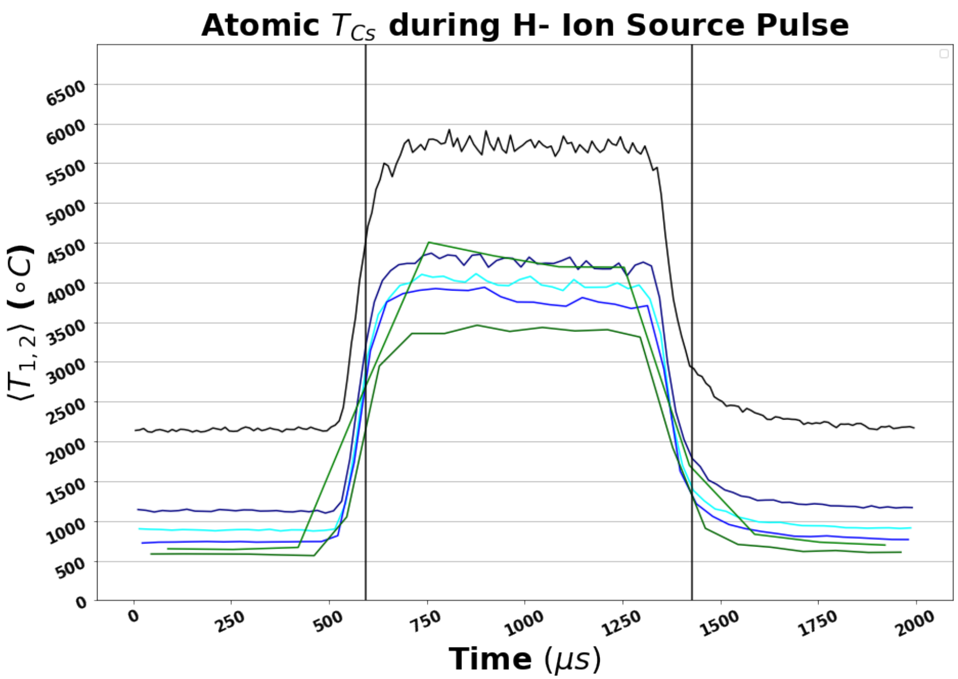
→ 6% difference. NOT AN ISSUE





Density & temp vs freq





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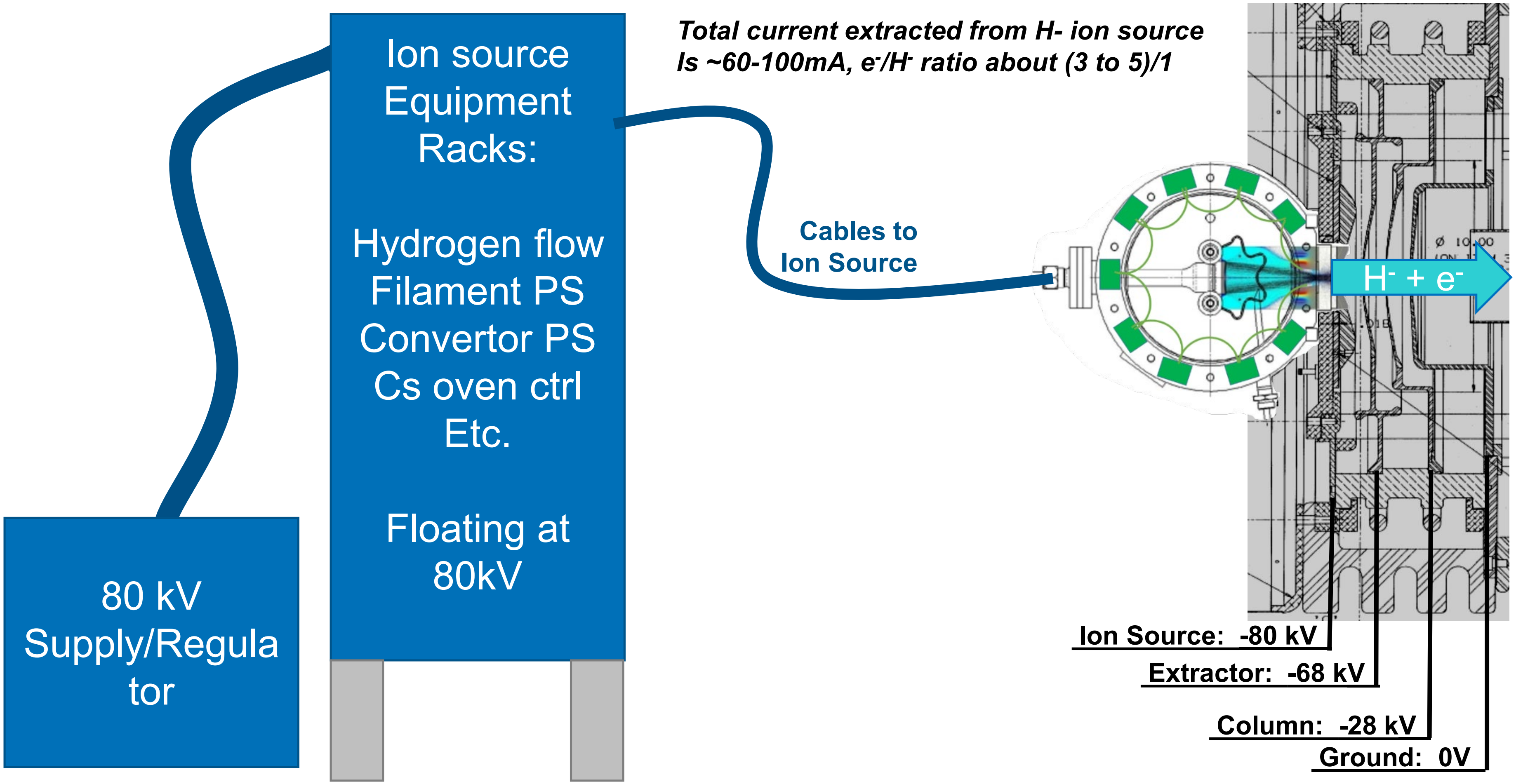
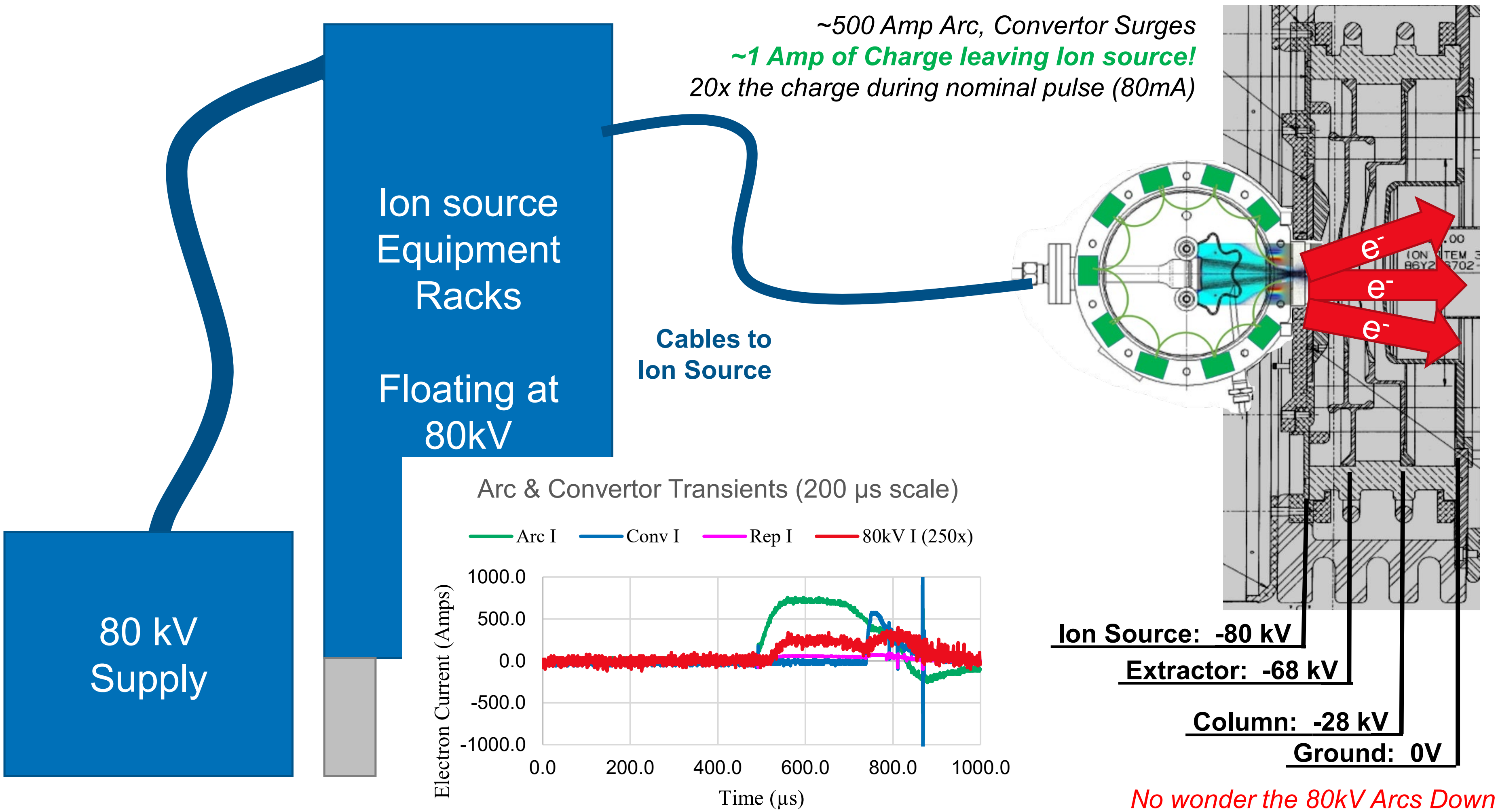
The LANSCE Multi-cusp Cesiated Surface-Conversion Source with initial 80 kV extraction



Large Transient observed with 80kV (June 2019)



This diagnostic provides needed insight while avoiding historical challenges

- Present diagnostics tools external/outside the ion source
  - **External** voltage/current monitors, thermocouples
  - Need large, cumbersome **HV** Injection to measure emittance, beam current
    - H- Ion Source Test Stand (ISTS) has become more of a (very successful) beam injection R&D tool in the last few years.
    - Safety: Radiation hazards
- New H- Ion Source Laser diagnostic stand looks directly **into** ion source
  - **No high voltage extraction** makes for “benchtop tool” for more efficient experiments
    - Safety: No radiation hazards (albeit we introduce laser hazards)
  - Fast resolution (as low as ~10 μs) to diagnose intra-pulse effects
- Establish the diagnostic for accelerator based ion sources(*)
- Invaluable data for global ion source community

- **(As far as I know)*

How will this novel diagnostic improve LANSCE programmatic needs?

- Understanding time-dependent signatures of the Cs density will provide valuable tool to improve stability issues
  - What is correlation between Cs density and instabilities related to arc current transients? [1]
- H- density will reveal the hidden neutralization mechanisms of H- ions inside the H- ion source.
  - I_{H-} = ~0.1 - 1 A (hypothesized) at convertor, but only ~0.015 A (measured) downstream? Factor of x100?
    - *Even recovering a small amount of neutralized H- could be revolutionary for LANSCE*
- Data for ion source modelling.

[1] Transients on Arc and Convertor currents in the Multi-cusp Cesiated Surface Conversion H- Source at LANSCE
2019 IEEE Pulsed Power & Plasma Science (PPPS), 2019, p. 1-4 (Kleinjan, D.)