Thomson scattering measurements on the Zap Energy sheared flow stabilized Z-pinch

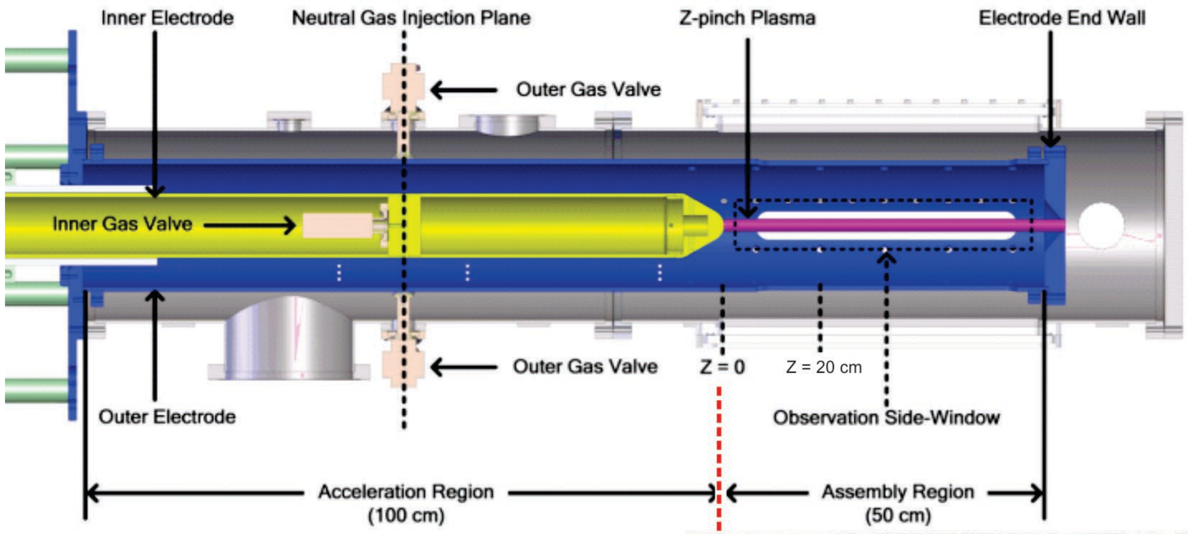
S. C. Bott-Suzuki, J. T .Banasek, C. Goyon. G. F. Swadling, B. Levitt, M. Quinley, B. A. Nelson, U Shumlak. H. S. McLean, A. E. Youmans, D. P. Higginson, C. Liekhus-Schmaltz, E. T. Meier, L. A. Morton, A. Taylor, W. C. Young, D. A. Sutherland, A. D. Stepanov, J. R. Barhydt, P. Tsai, K. D. Morgan, N. van Rossum, A. C. Hossack, T. R. Weber, W. A. McGehee, P. Nguyen, A. Shah, S. Kiddy, M. Van Patten, G. A. Wurden

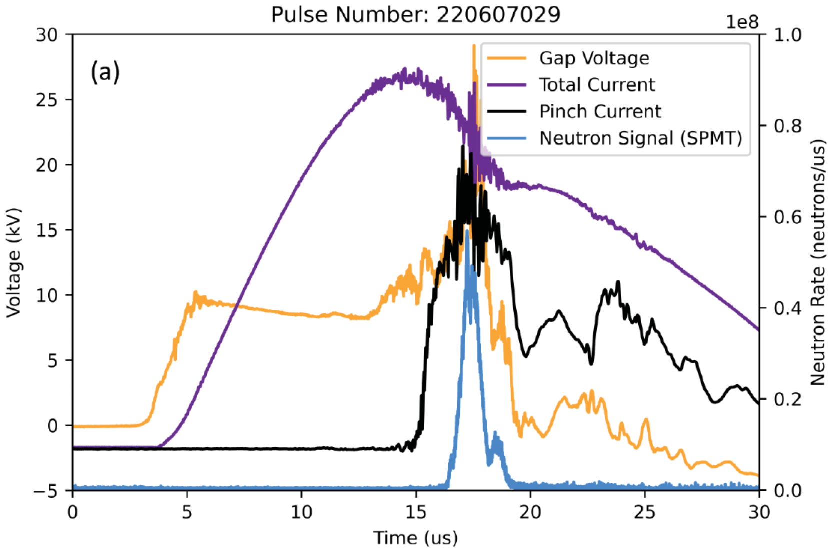
+ the ZaP Energy Team, + the PANDA team

The sheared flow Z-pinch at Zap Energy

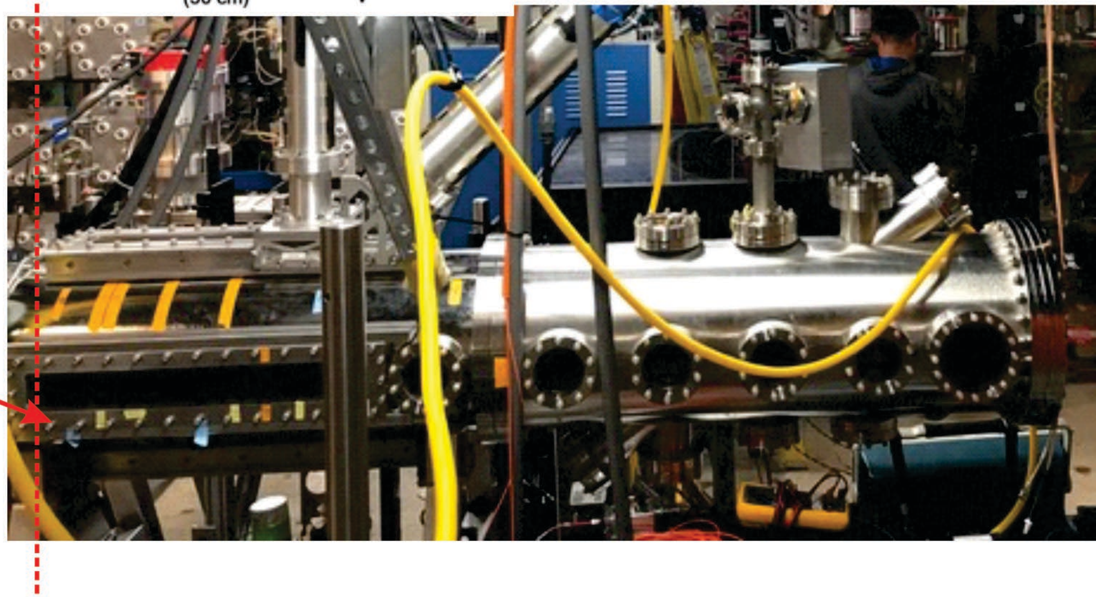
FuZe produces a large scale (50cm), long lived (>µs) fusion plasma (DD) stabilized well beyond MRT growth timescales by a radial velocity shear

zapenergy.com

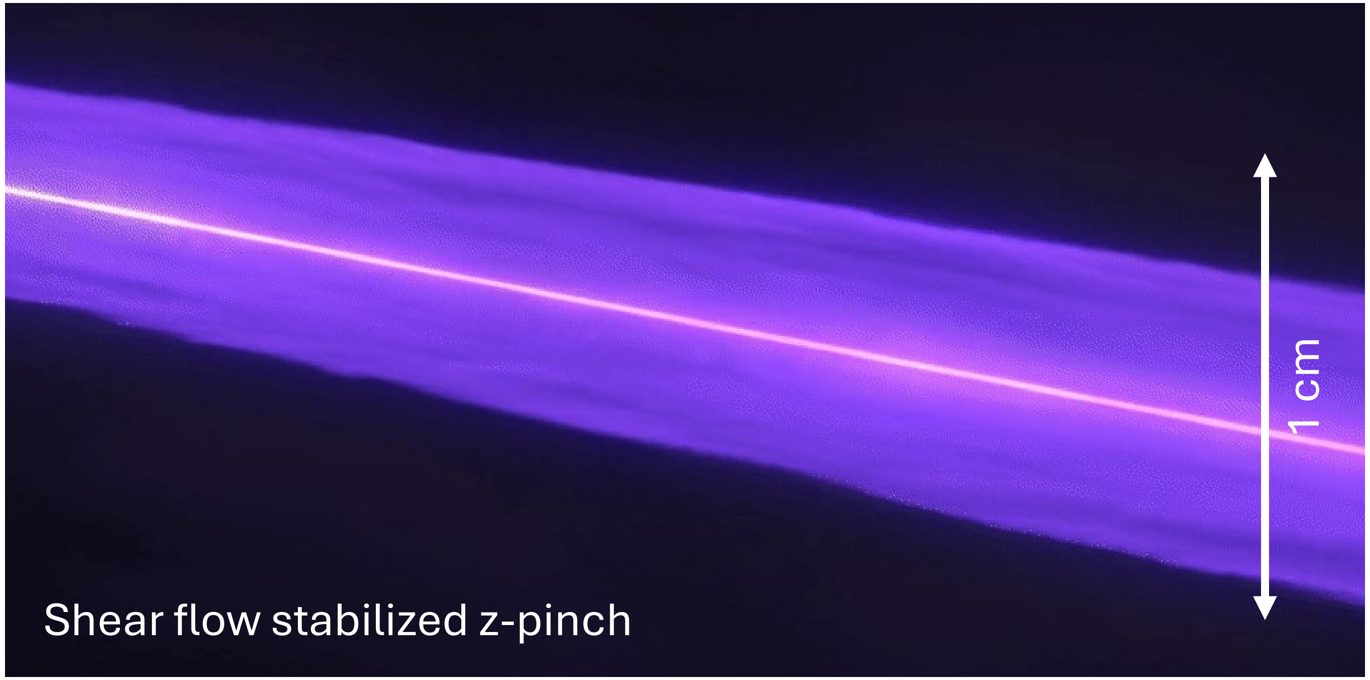


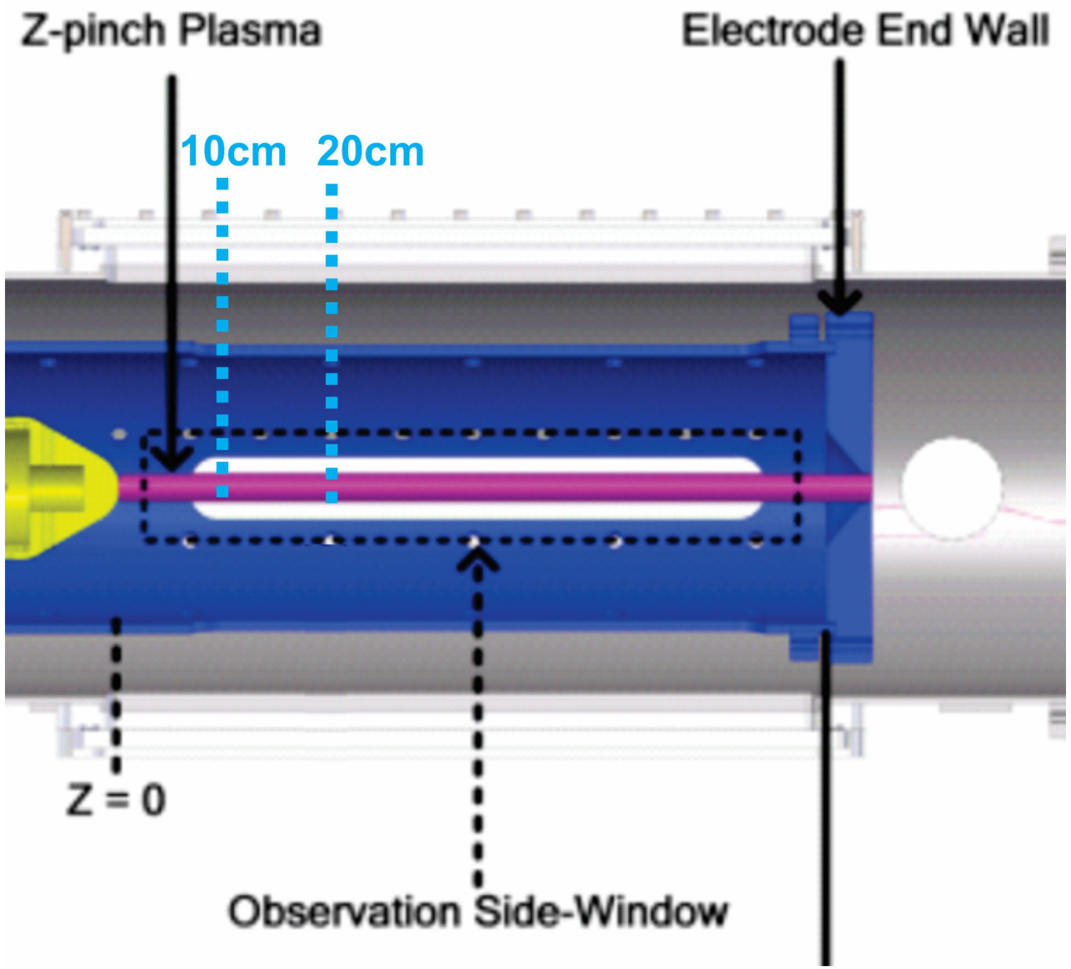


Diagnostic access flanges to be replaced with custom OTS design



Aim is to characterize plasma conditions at 2 locations





- Compare n_e, T_e to neutron signals to determine coincidence

Design considerations for FuZe

Optimizing signal

- ***T_e and density and expected*** (>1 keV, >1x10^{17} cm^{3})

$\alpha = 1/k\lambda_{De}$ $\quad\quad$ $\alpha \propto \sqrt{n_e/T_e}$ → Borderline Collective / Non-Collective

- ***Scattering geometry***

- ***Scattered light issues***

- ***Emission lines in the collection spectral range***

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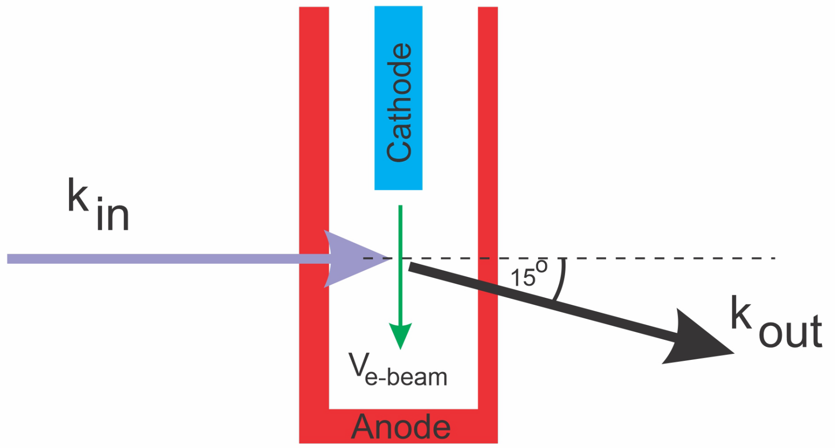
Borderline Collective / Non-Collective

$k = k_{out} - k_{in}$

- ***Scattering geometry***



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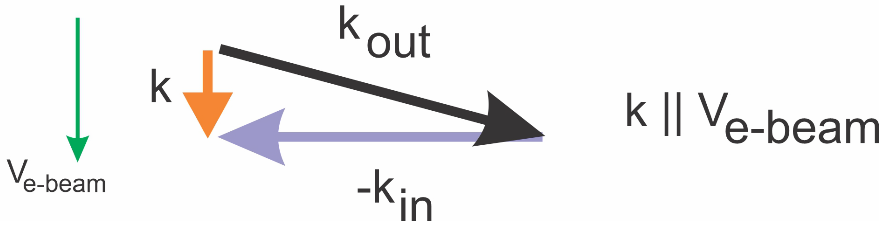

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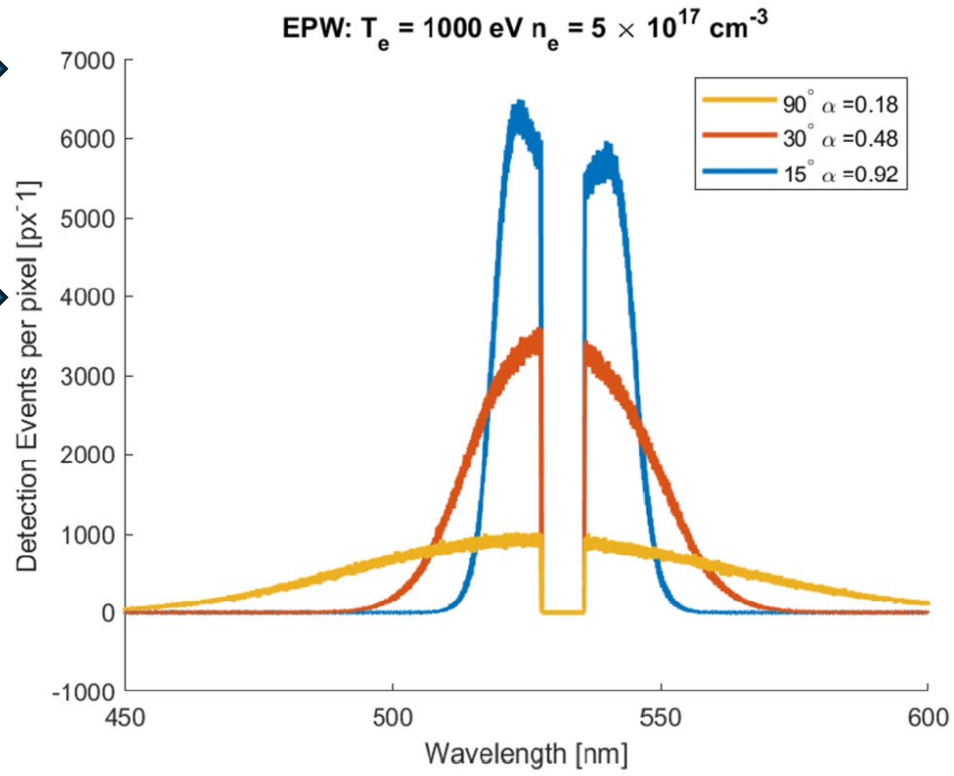
→ Borderline Collective / Non-Collective

- ***Scattering geometry*** →

- ***Scattered light issues*** → Notch Filter 17nm FWHM →



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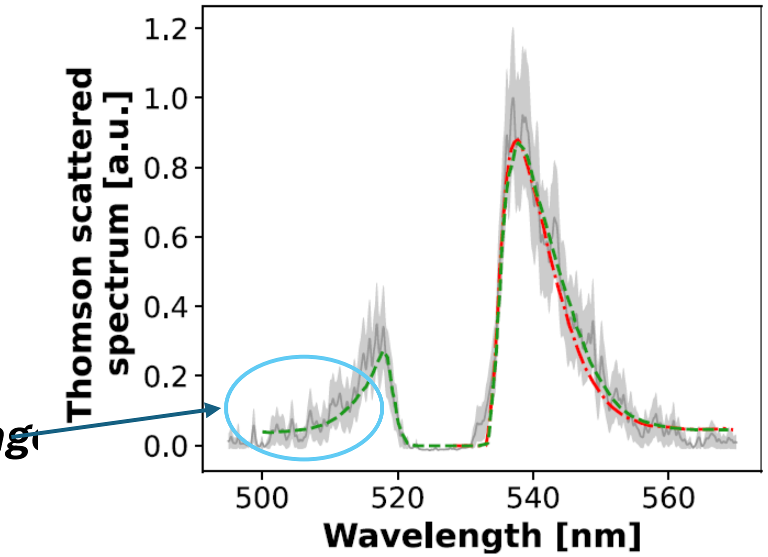
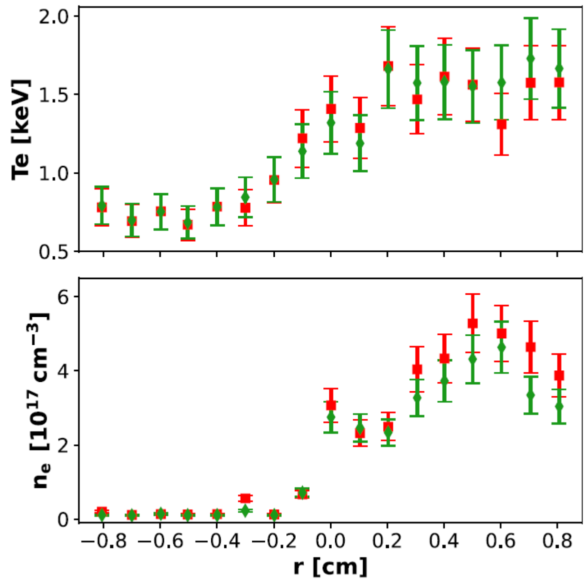
- ***Scattering geometry***

- ***Scattered light issues***

- ***Emission lines in the collection spectral rang***





Design considerations for FuZe

Experimental challenges

- ***Chamber compatibility***
  Input, collection, beam dump, alignment x 3
  LOS for other diagnostics (interferometry, emission)

- ***Targeting the plasma***

- ***Alignment***

- ***Portability***

Design considerations for FuZe

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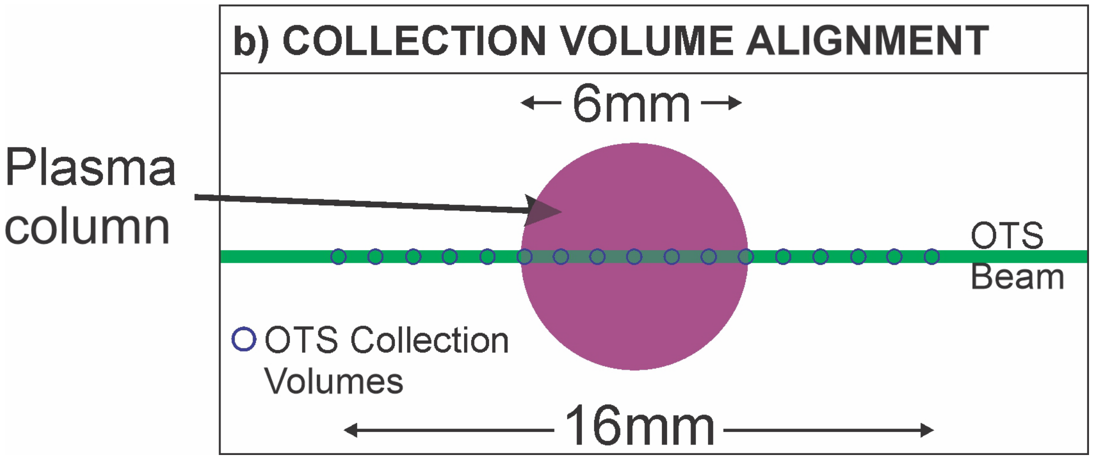
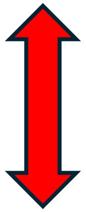
- ***Targeting the plasma***
  Plasma column shows variation in position along the TS view



- ***Alignment***

Good compensation for motion along the laser path



Poor compensation for motion perpendicular to the laser path

- ***Portability***

Design considerations for FuZe

Experimental challenges

- ***Chamber compatibility***
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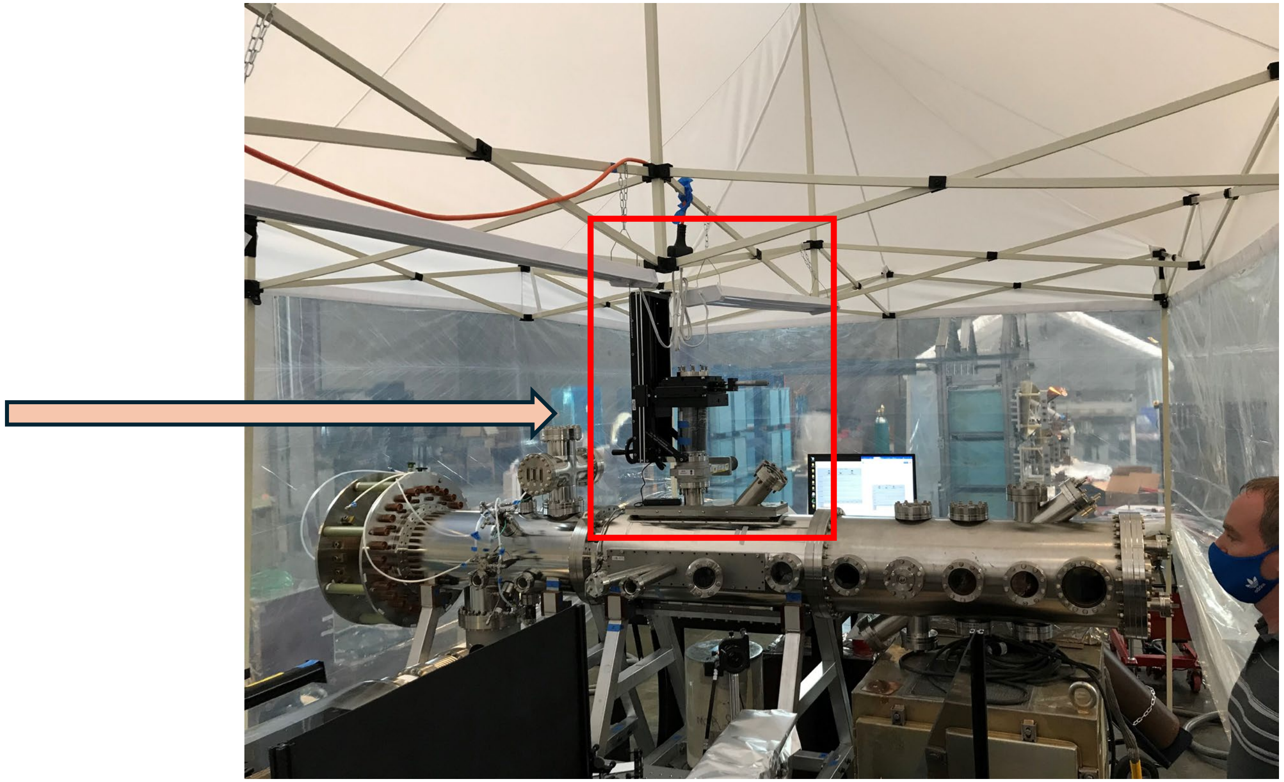
  Plasma column shows variation in position along the TS view
- ***Alignment***
  Repositioning accurate to 10μm over 14" travel
  Protected behind gate valve between uses
- ***Portability***



Design considerations for FuZe

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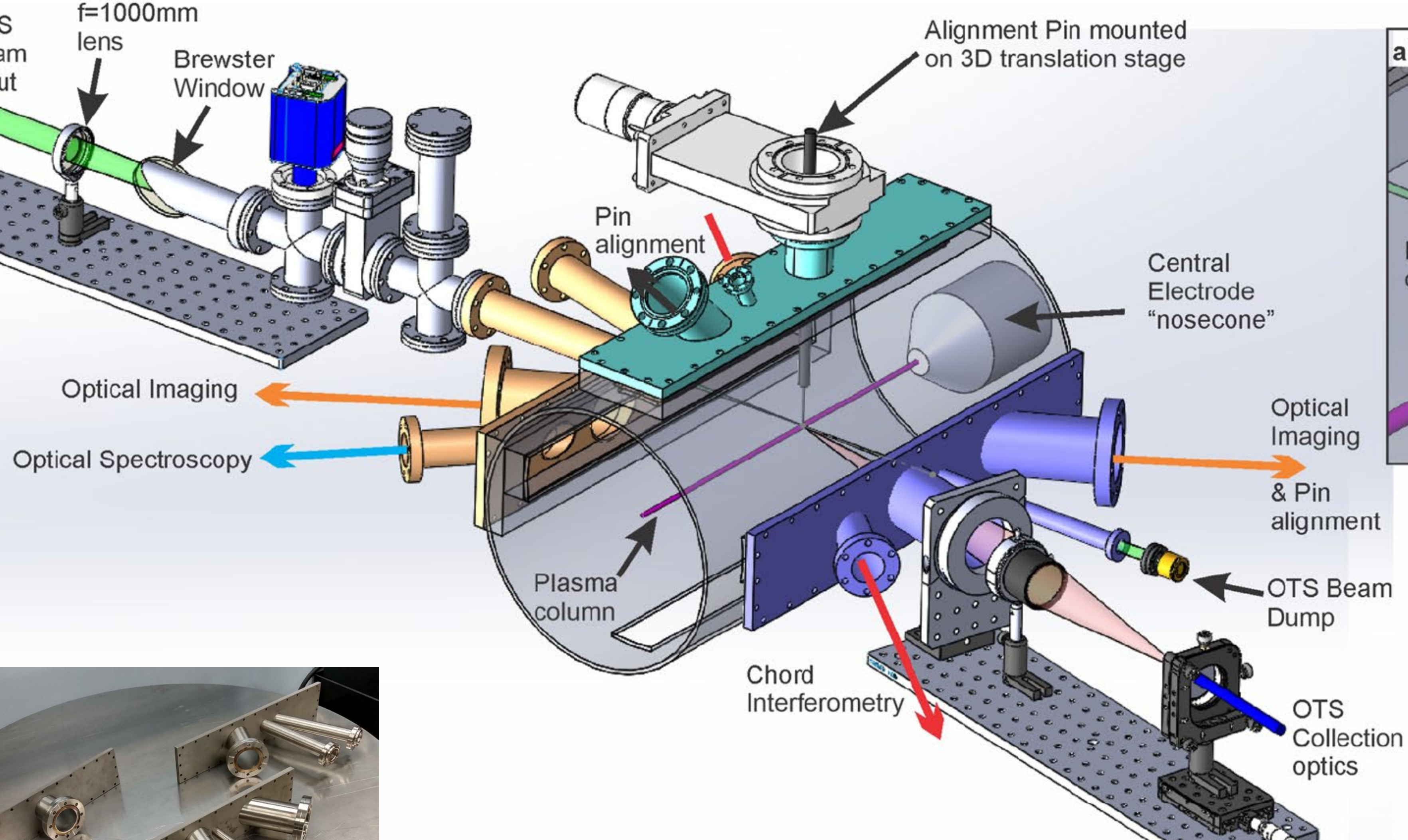
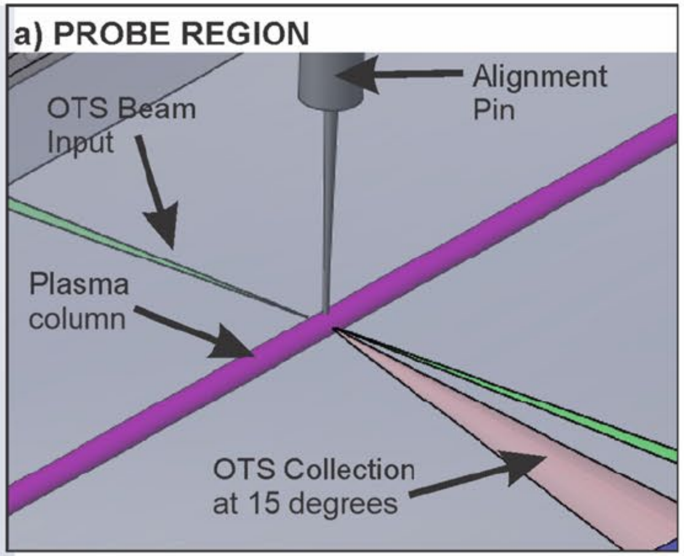
- ***Alignment***
  Repositioning accurate to 10μm over 14” travel
  Protected behind gate valve between uses

- ***Portability***
  Repositioning relative to pulsed power useful
  Project was to build portable system…

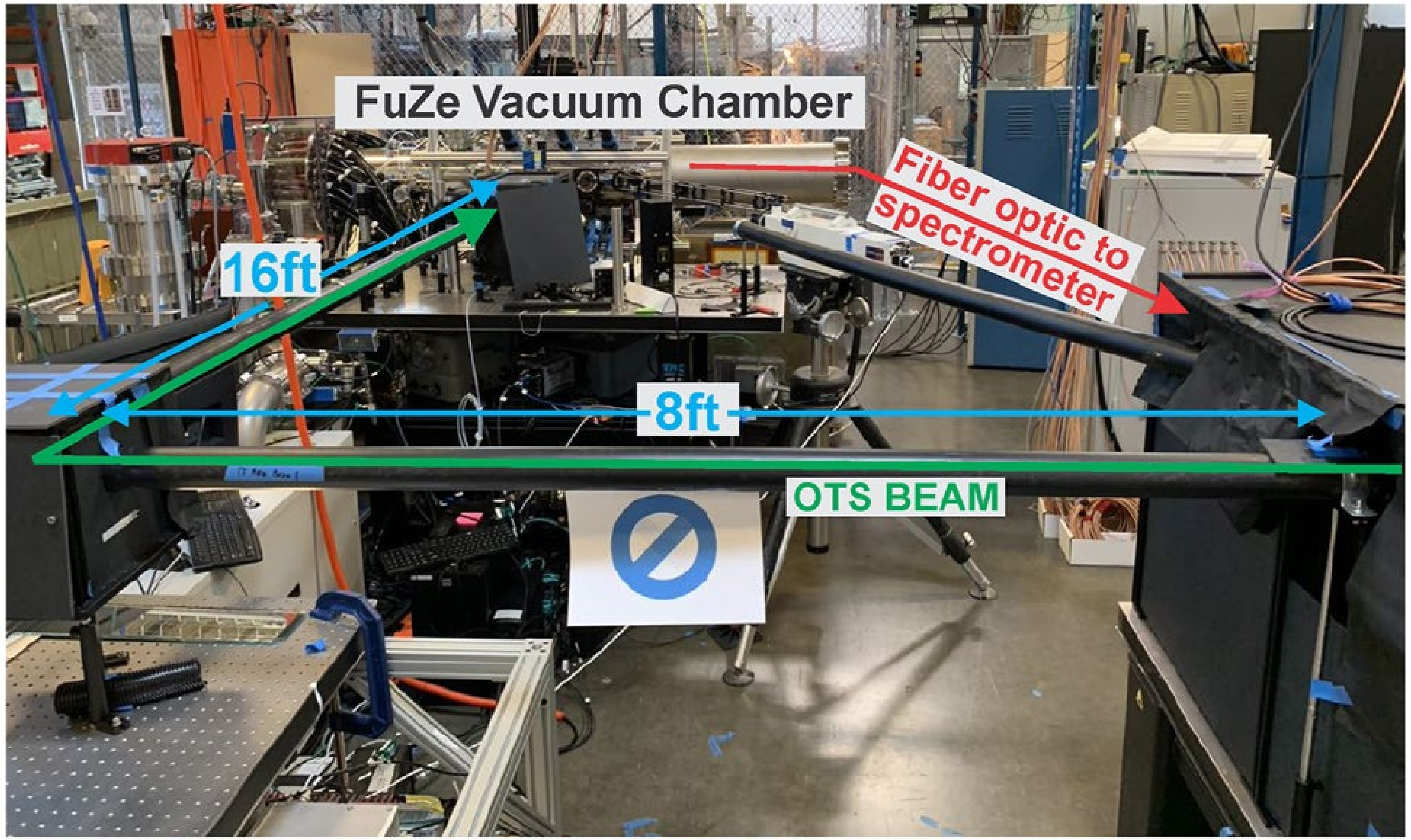
Final Engineering Design for FuZe

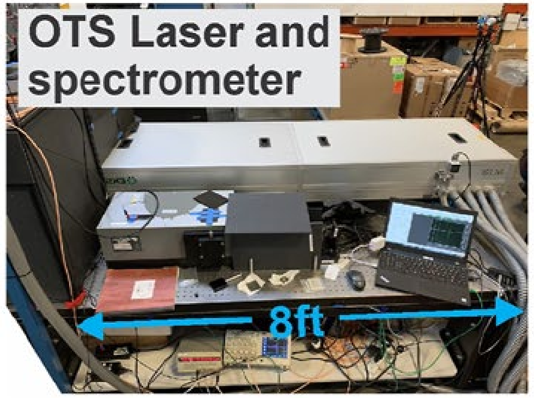


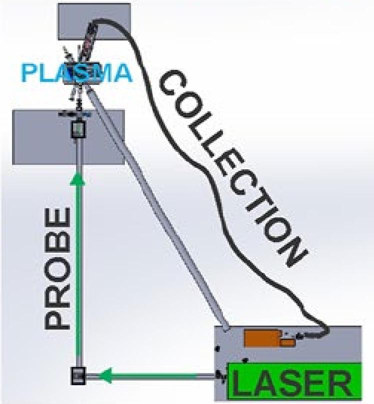


Final Engineering Design for FuZe

- Ekspla NL129 Nd-YAG at 532nm, 8 J in 1.5 ns
- Andor 500 mm Shamrock Czerny–Turner spectrometer with Andor iStar CMOS detector (4ns gate)
-
- For EPW, a low-resolution grating (150 L/mm) gives sufficient bandwidth
- Fiber optics collection, 17 fibers (f/4), 100μm cores
- Collection volume of 0.25 × 0.25 × 0.74 mm^3, and the total field of view for all 17 fibers is 16 mm
- Laser, spectrometer(s), trigger units, oscilloscope, DGG, control PC all fit on one 8’x4’ optical bench on wheels



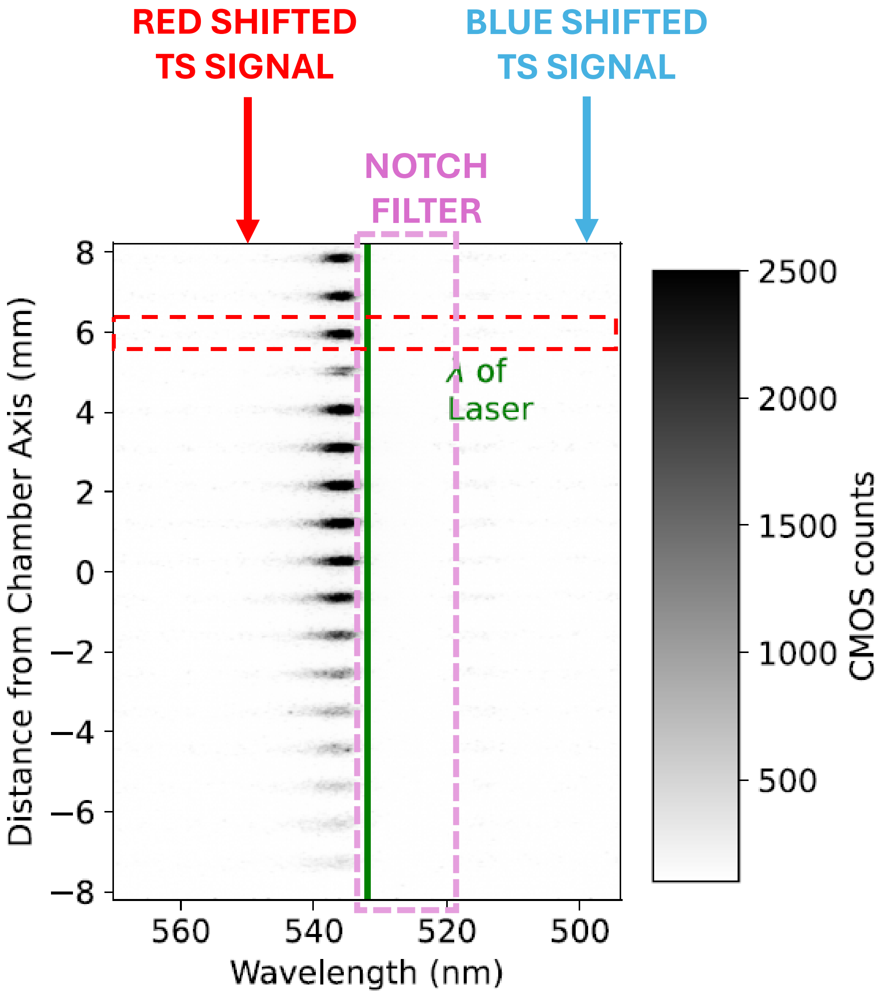


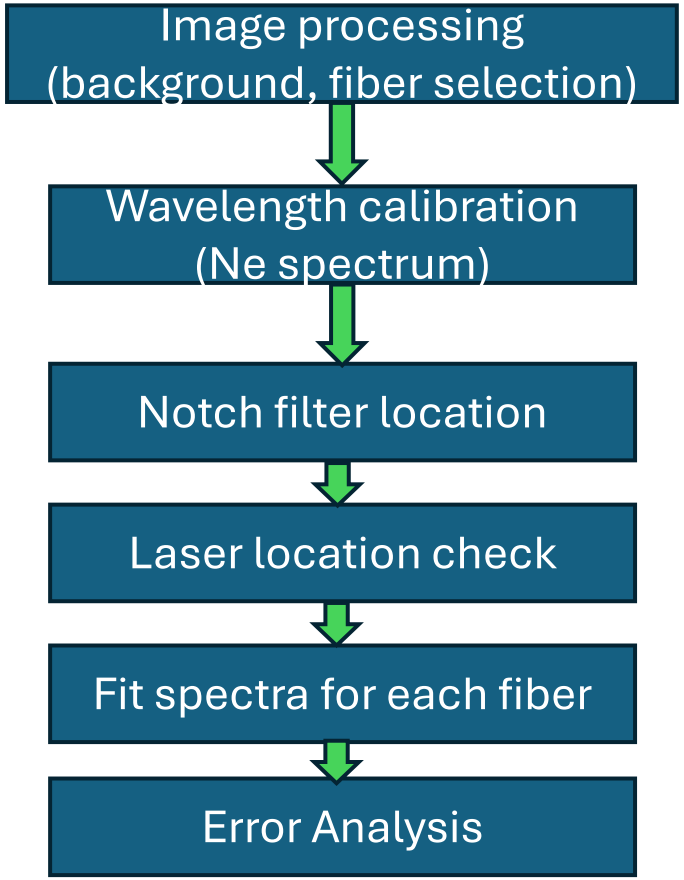


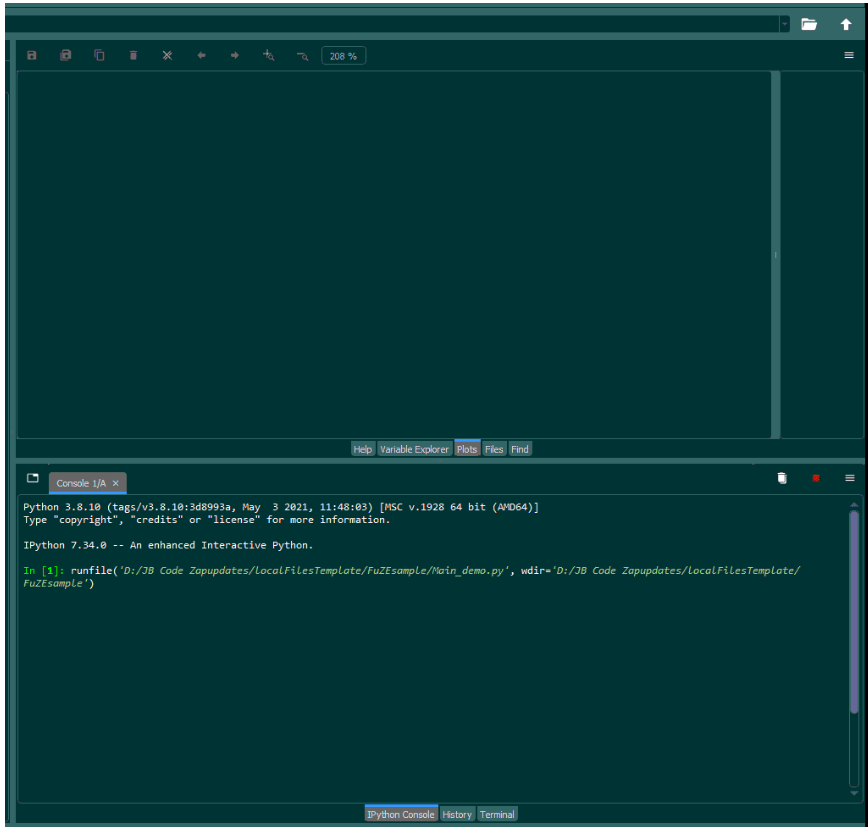
Thomsonpy: automated, iterative fits to data with error bars

Fit routine is from Jacob Banasek

Banasek, J. T., Byvank, T., Rocco, S. V. R., Potter, W. M., Kusse, B. R., & Hammer, D. A. (2018). “Time-Resolved Thomson Scattering on Laboratory Plasma Jets”, *IEEE Transactions on Plasma Science*, 3901 - 3905



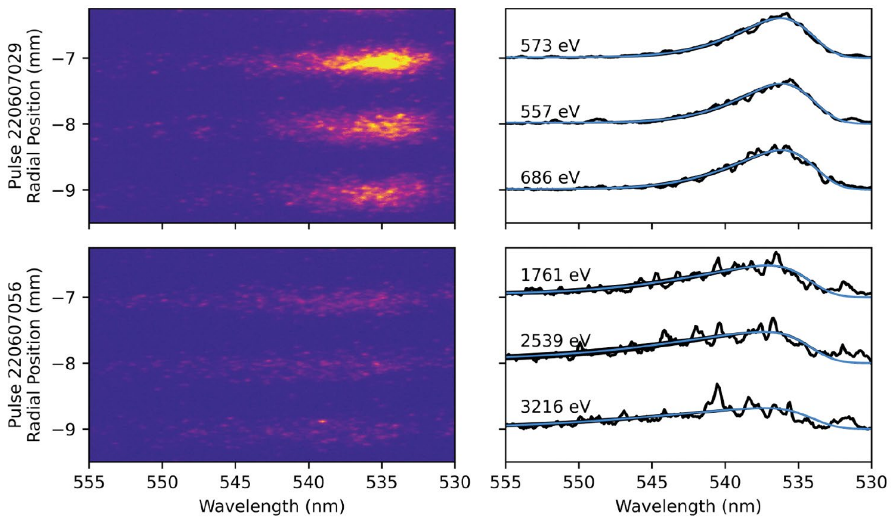


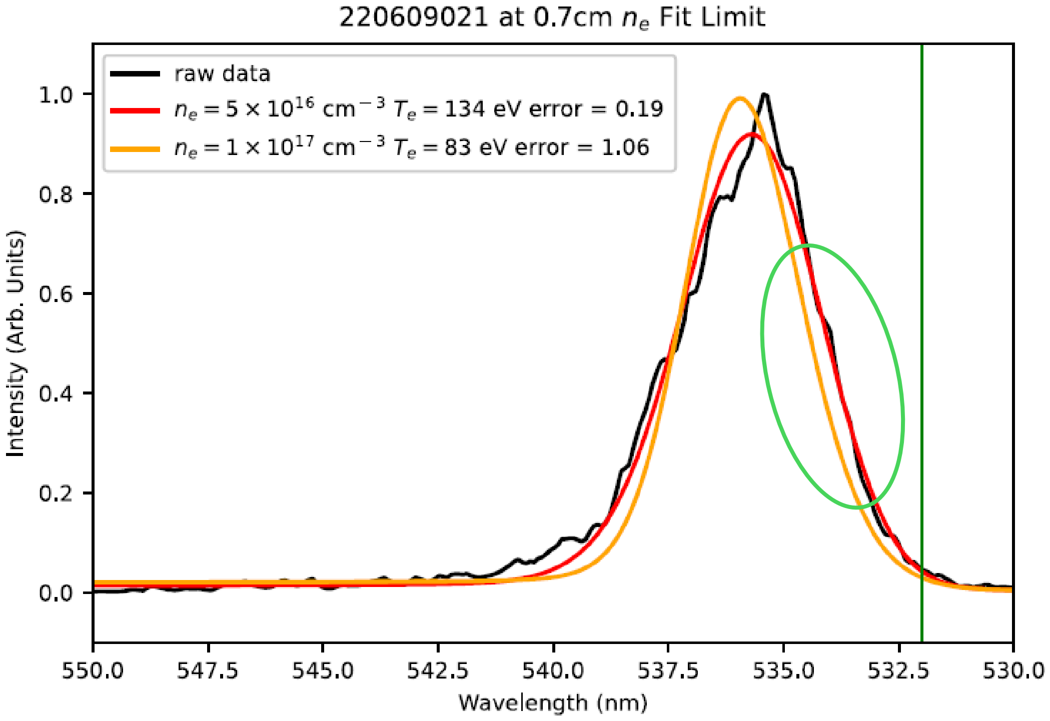


Error bar determination

- Developed after initial data sets taken to assess plasma conditions
- As measured Te increase the total scattered intensity decreases (proportional to ne)
- So, the lowest Te shot are at the highest density (highest scattering intensity)
- Can use these to determine the maximum density for the data set
- From test fits, we find that density can be no larger that $5x10^{16}$ cm^{-3}

UPPER DENSITY BOUND = $5x10^{16}$ cm^{-3}





Error bar determination, and final T_e data

- As the plasma T_e increases and density drops, the system becomes more non-collective
- Eventually density plays no role in the fit so we can set a lower (influential) density for the dataset

LOWER DENSITY BOUND = 5×10^{15} cm^{-3}

- The data is fitted using a non-collisional TS model (T_e, peak intensity, continuum level)
- Error bars on each fits use 1000 MC sims varying instrumental function (15%), the accuracy of the laser wavelength (1nm), dispersion of the spectrometer, by (1.5%), plus noise (inc. gain)
- We perform these fits at both the max and min densities from above to give 2 fits, and average these to give a final error bar on T_e

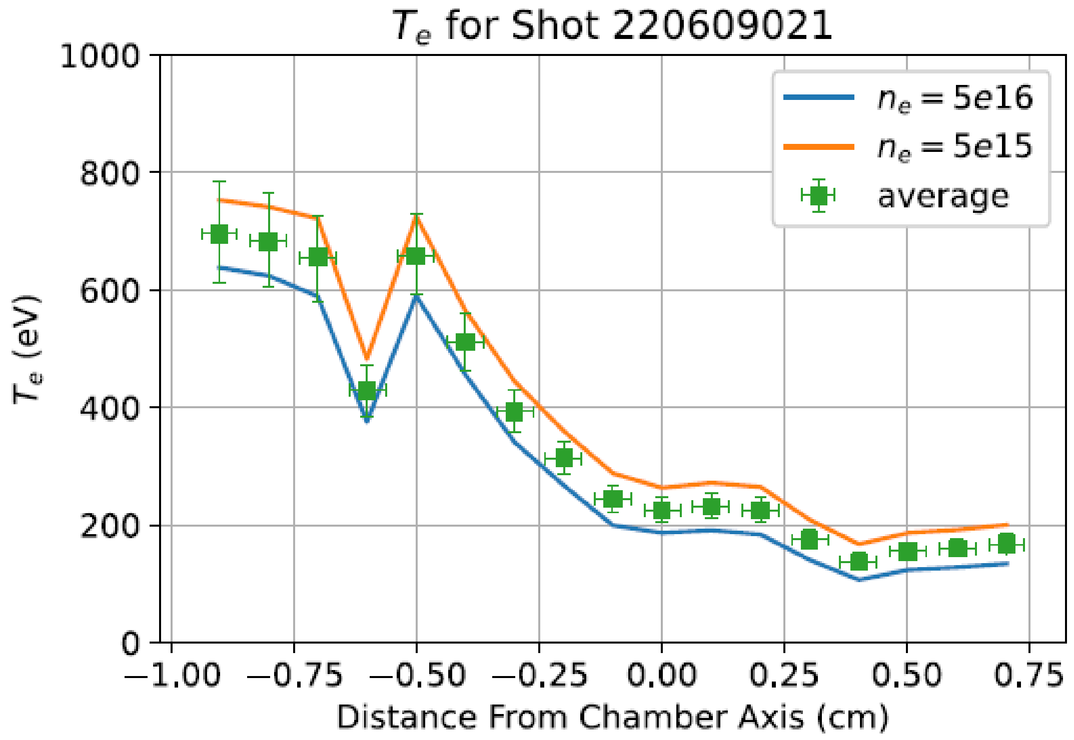
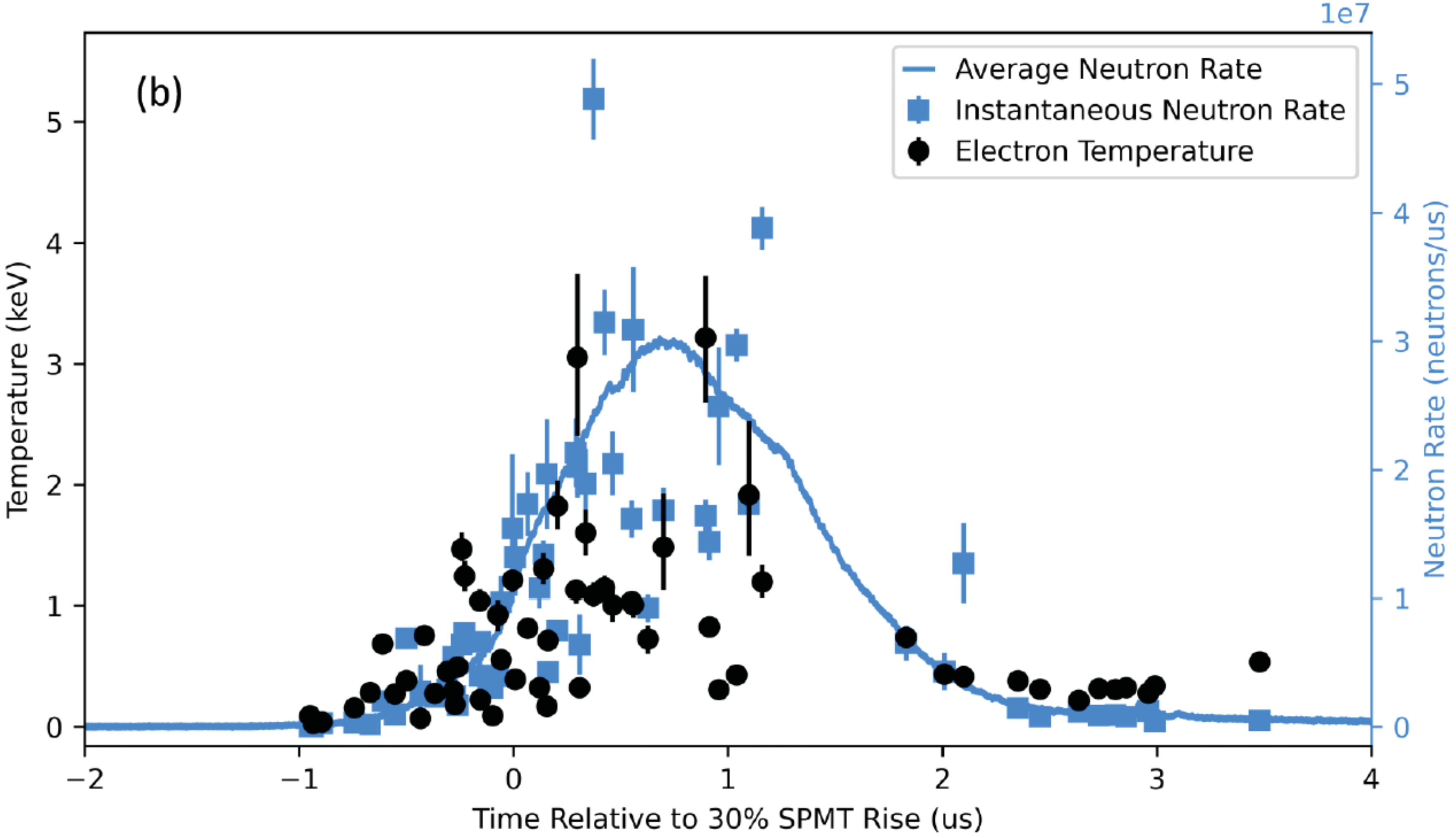


FIG. 11. Measured T_e for shot 220609021. Blue line is the fit at $n_e = 5 \times 10^{16}$ cm^{-3}, orange line is the fit at $n_e = 5 \times 10^{15}$ cm^{-3}, and the green points are the average of those two fits, with the error bars based on the Monte Carlo error calculations for the two fits. The horizontal error bars are the FWHM of each fiber.

Density can only be quoted to < 5×10^{16} cm^{-3}

T_e data trends coincident with neutron pulse

- ~250 shots in this series (up to 90 shots per day)
- Significant shot-to-shot variation, but clear rise in T_e during neutron production time
- Note that early and late time temperatures are always low
- Peak temperatures up to 3 keV

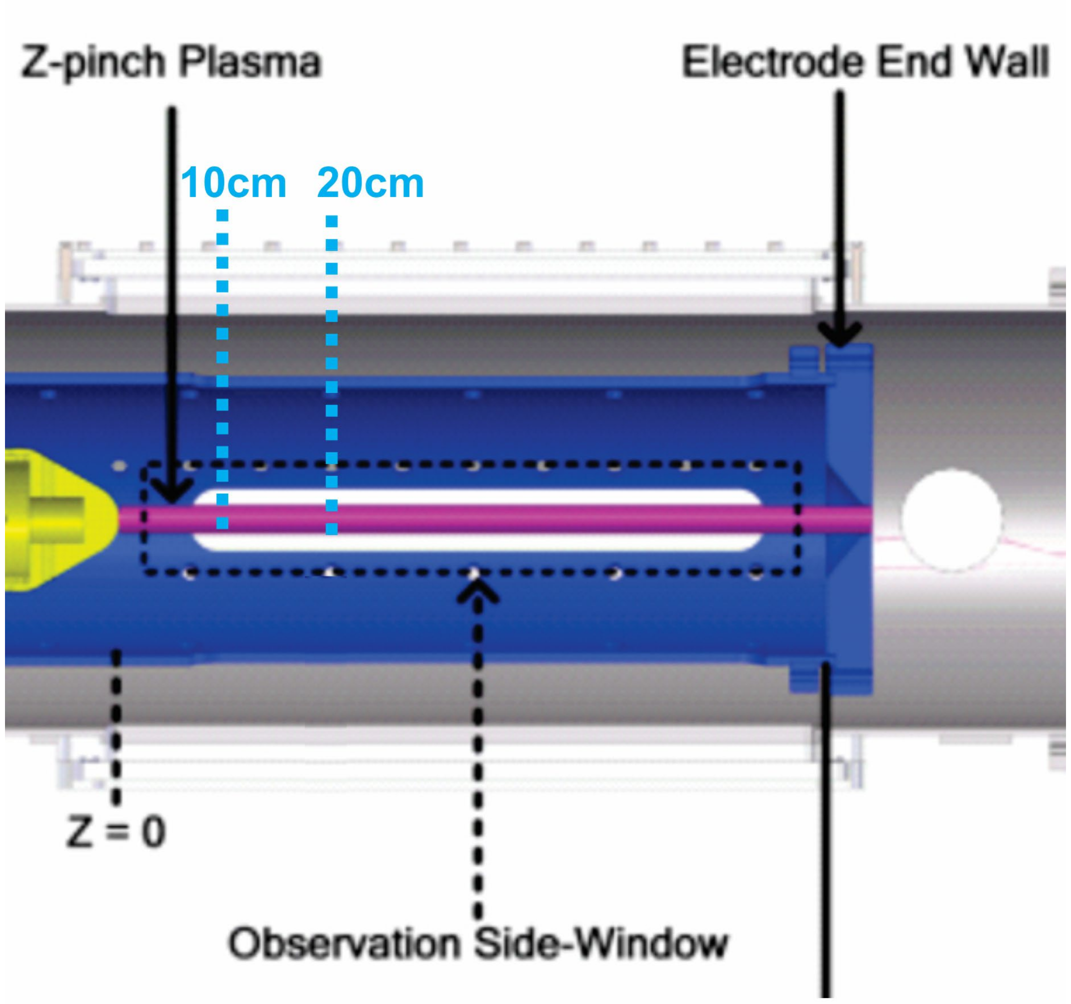


Comparative measurements along the z-pinch plasma

- Measurements closer to the central “nosecone” electrode provide additional information

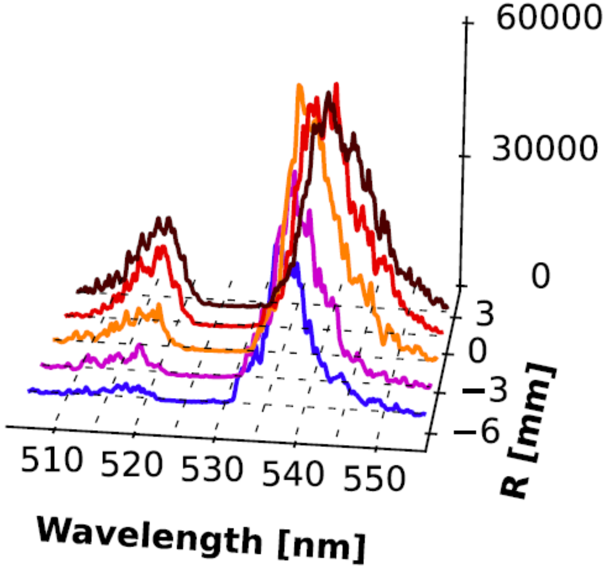
- Possibility of higher density here, enabling more data recover from TS fits

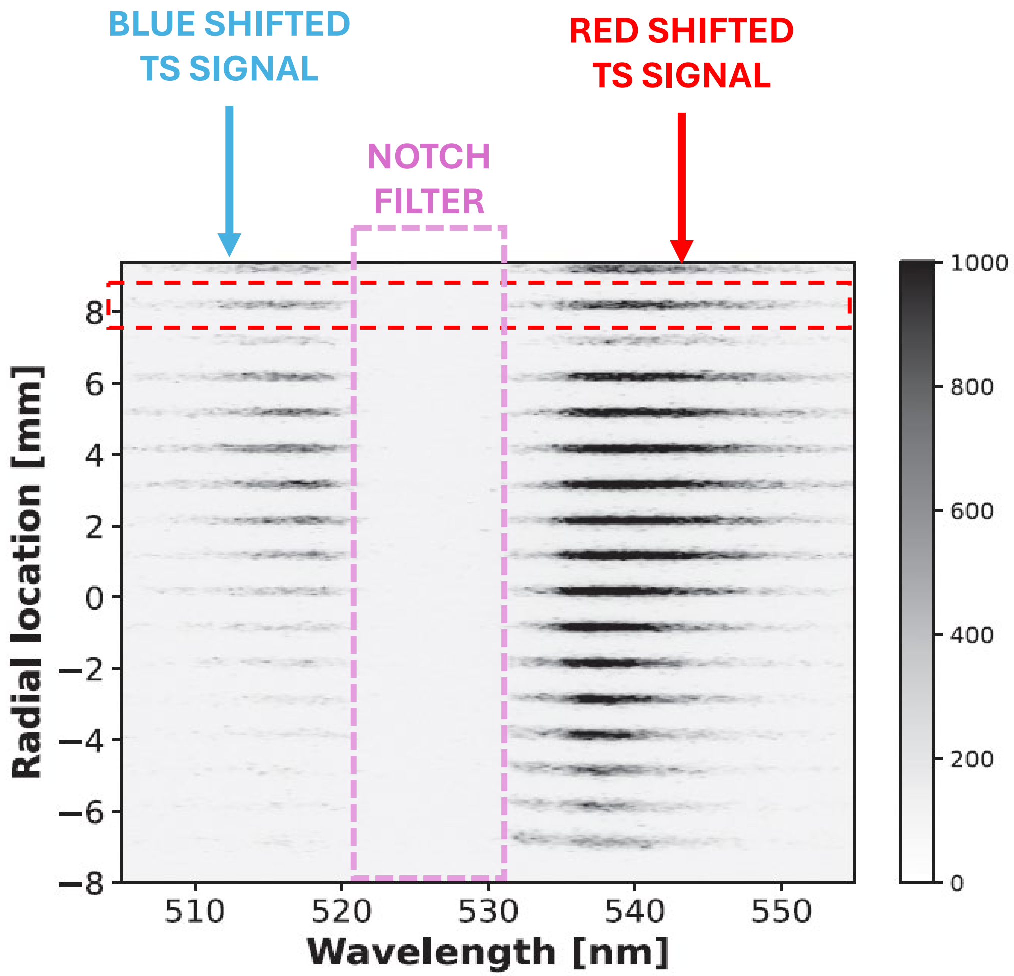
- New vacuum flanges for p=10cm designed and constructed to translate setup along the z-axis



Data at p=10cm shows good signal trends

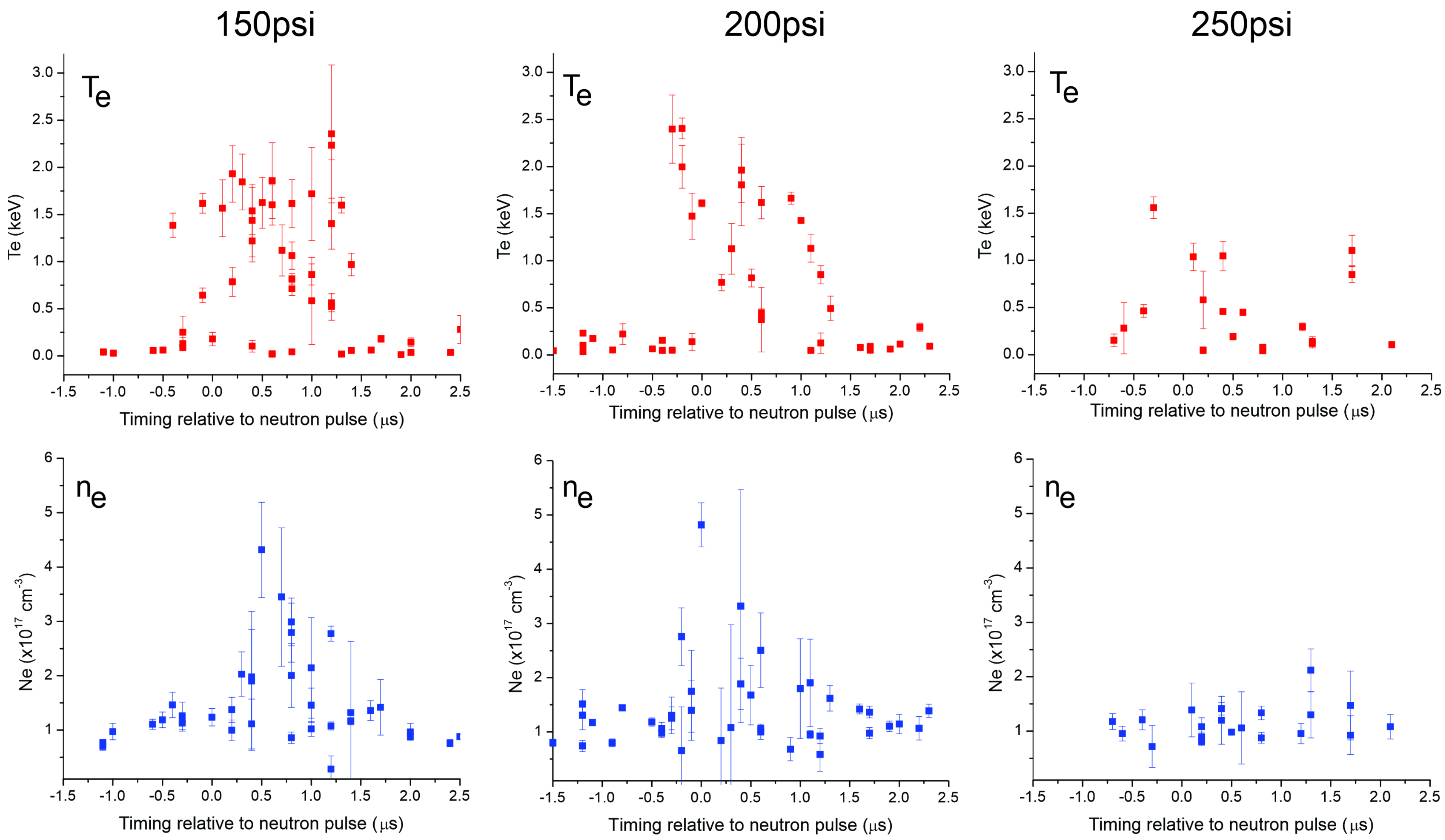
- High T_e values again measured for a wide range of shots
- Correlated with high scattering signal strengths, meaning likely increasing density here too
- Scanning D_2 fill pressure helps elucidate what is driving the fusion condition producing the neutron pulse





Pressure scan through neutron emission time shows T_e, n_e trends

- ~250 shots in this series over 3 fill pressures
- Te data consistent with p=20cm but shot-to-shot slightly better
- First measurements of ne in this work
- Density for 150psi and 200psi shots increases during neutron pulse



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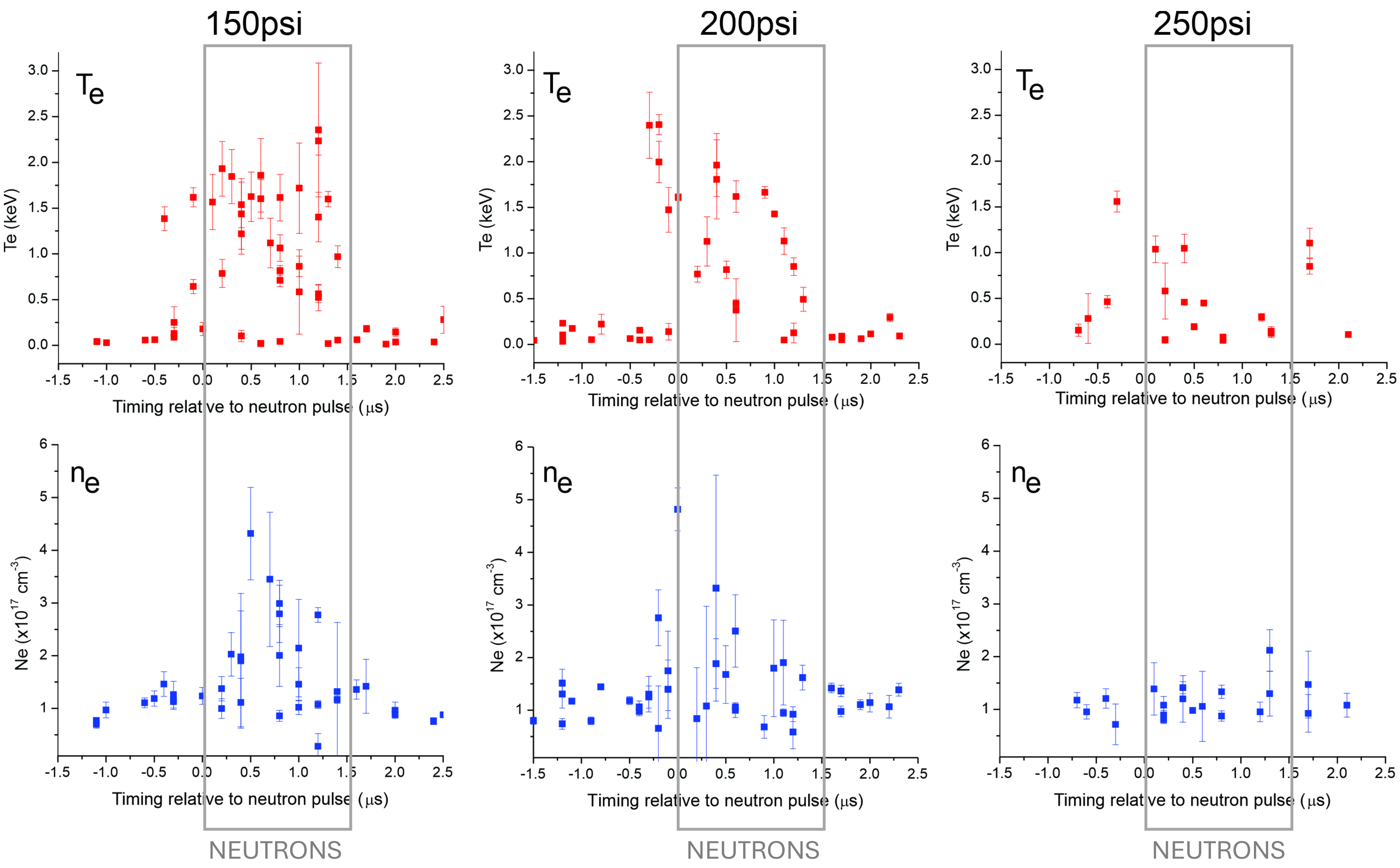
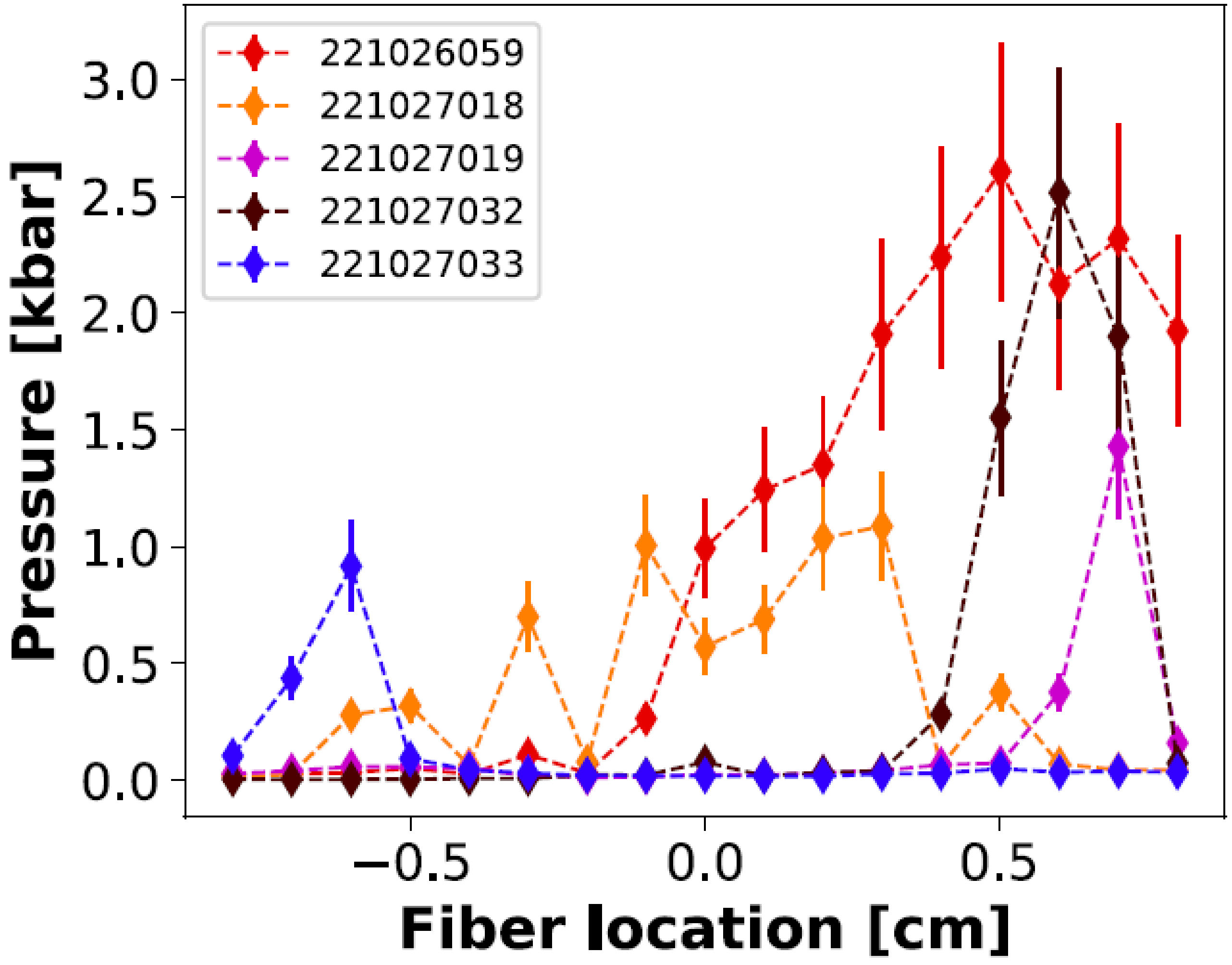


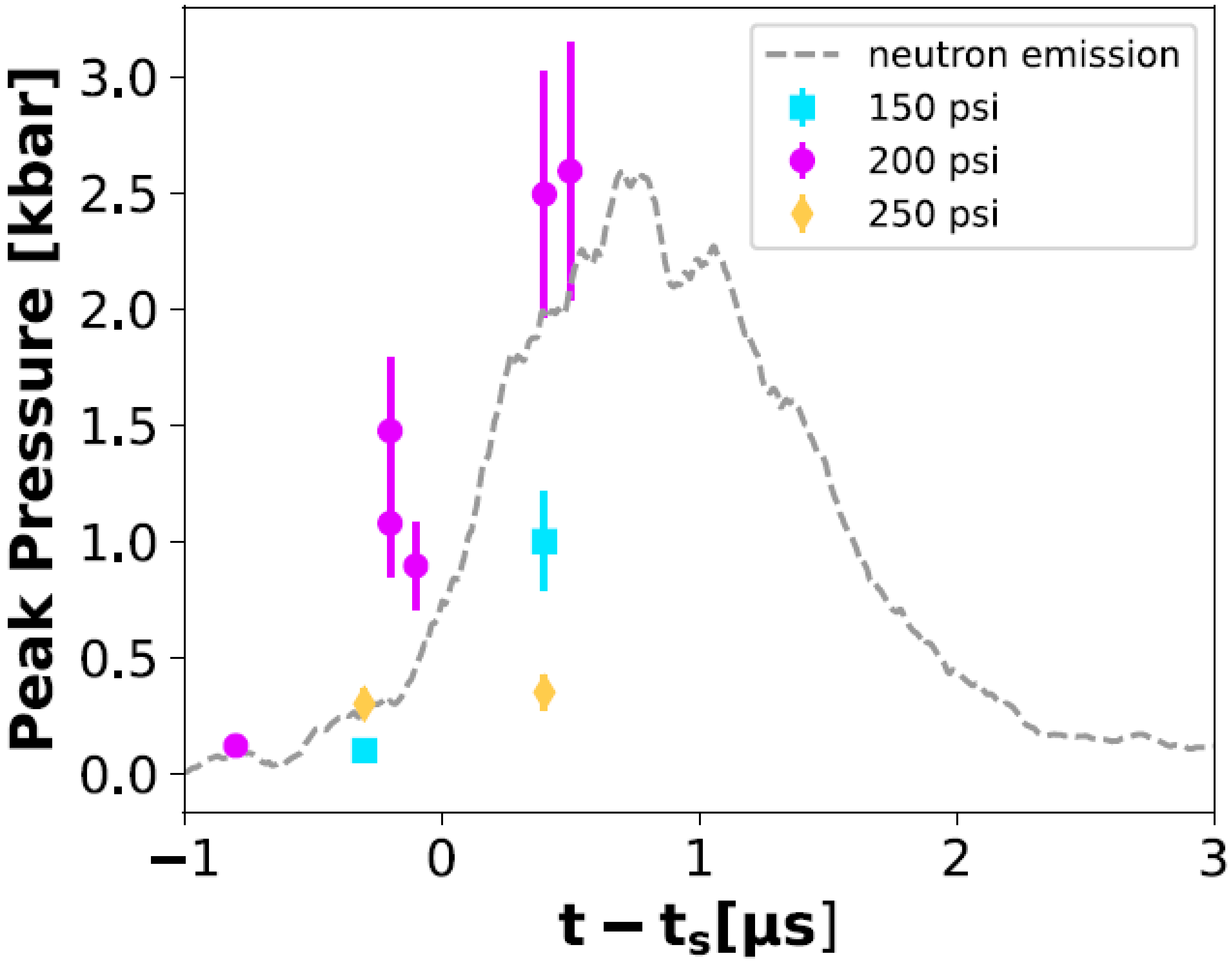
Reconstruction of pressure profile shows plasma column

- TS data shows the formation of a small diameter plasma column at high pressure
- Column diameters varies from 1mm to 10mm for shots with pressures >kbar
- Still significant shot-to-shot variations
- Comprehensive study being carried out at Zap Energy on upgraded driver



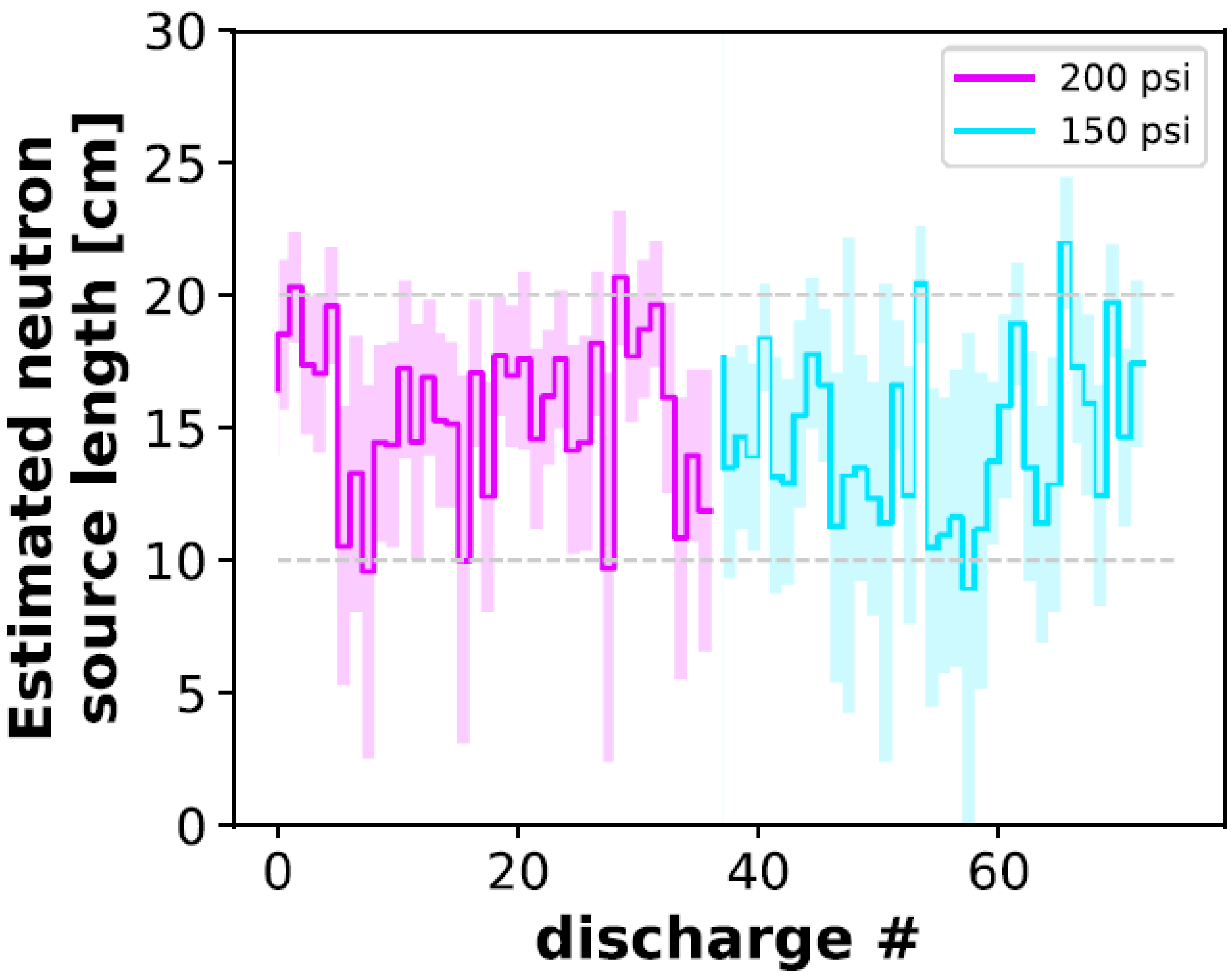
Peak pressures with time track neutron pulse

- Peak column pressure is plotted against the neutron signal (where available)
- In each case, the increase in pressure is coincident with an increase in the instantaneous neutron production rate



Comparison of TS data to spatially resolved neutron data

- Neutron detectors are placed along the length of the pinch, and relative signal strength used to approximate the length of the neutron producing region
- Generally, the ‘active’ pinch region falls between the two TS measurement location
- Explains the ability to recover density data at p=10 and better plasma column hit-rate.



Summary

- TS data successfully recovery from 2 locations in the Zap sheared flow Z-pinch
- Robust data reduction and error analysis routines developed
- TS system is portable, can be designed and deployed on different experiments

J. T. Banasek *et al, Rev. Sci. Instrumen.*, 94, 023508 (2023)

- Despite low densities at p=20cm, T_e data showed trends coincident with the measured neutron pulse and keV peak temperatures

B. Levitt *et al, Phys. Rev Lett*, 132, 155101 (2024)

- Data at p=10cm showed measurable n_e and T_e data during neutron pulse consistent with increase in plasma pressure
- Peak values were 2.25 +/- 0.8 keV and densities up to 4.9 +/- 0.2 x 10^{17} cm^3

C. Goyon *et al, Phys. Plasmas*, 31, 072503 (2024)