A Suite of Plasma Diagnostics for FuZe at Zap Energy

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A whole team of people make these measurements and analysis possible

- Aria Johansen, Uri Shumlak; **U of Washington**
- Anton Stepanov, Andrew Taylor, Nolan van Rossum, Chelsea Liekhus-Schmaltz, Lucas Morton,Tobin Weber, Morgan Quinley, Daniel Garratt, Ben Levitt, Brian Nelson; **Zap Energy**
- Thomas Weber, John Dunn; **LANL**
- Adian Klemmer, Bruno Bauer, Stephan Fuelling; **U of Nevada Reno**

LANL/UNR have two ARPA-E Diagnostic Capability Team Awards (TINA & BETHE)

- Originally, we planned to take diagnostics to more than one ARPA-E plasma experiment….. but:
- The reality of experimental physics, including interpreting data which then demands experimental/diagnostic modifications and iterations, have in fact caused us to focus on only one facility….namely FuZe at Zap Energy.
- We were further constrained to only one partner in the past two years, due to the necessity of putting public-private paperwork in place, the impact of Covid constraints, learning to operate fully remotely*, and conducting operations at two different physical sites (U of Washington, and now Zap Energy's new facility in Everett).

*Figuring out remote operations capabilities actually turned out to be a positive thing, enabling much closer support/interactions than just a few physical trips would have provided.

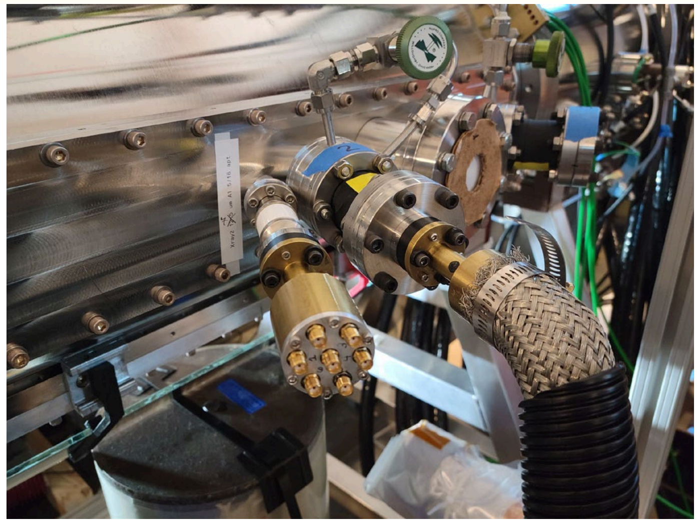
We have focused our efforts at Zap Energy

- **Fast imaging, spectroscopy, and x-ray measurements**
  – Custom vacuum access flanges for FuZe
  – Hadland 200 Million fps intensified camera, 4-channels of PMT based filtered x-ray phosphor detectors, x-ray filtered phosphor-based pinhole camera
  – U of Nevada (Reno) extreme ultraviolet (EUV) spectrometer to be installed this summer
  – Switched over to compact 7-channel XUV diodes with Femto preamps for filtered x-ray measurements from a single port location (two systems)
  – Modified x-ray pinhole camera with sensitive PCO-C1 camera for acquisition

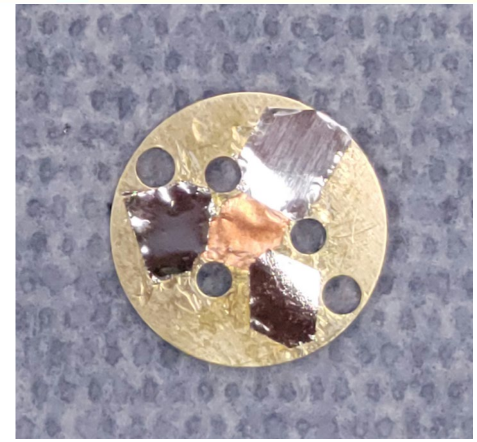
- **Spectroscopy, more x-ray imaging, neutron measurements**
  – Multichord visible spectroscopy (McPherson 218, PiMax-2 camera, 6-chords)
  – Obtaining/testing German X-Spectra AGPID 352-frame solid state x-ray camera
  – Arsenic neutron activation detector (1) and Rhodium neutron activation detectors (3)
  – Other PMT-based real-time neutron detectors (NE912 Li6 glass, Eljen EJ-301 liquid, ZnS:Ag proton recoil scintillators)

Calibrated soft x-ray (XUV7) diodes at FuZe

XUV7 diode array from LANL contains seven 0.2 mm x 0.2mm HS-1 AXUV photodiodes, with vented filter attachments



Multiple diagnostics view a common point at Z=+20 cm on the LANL vacuum flange



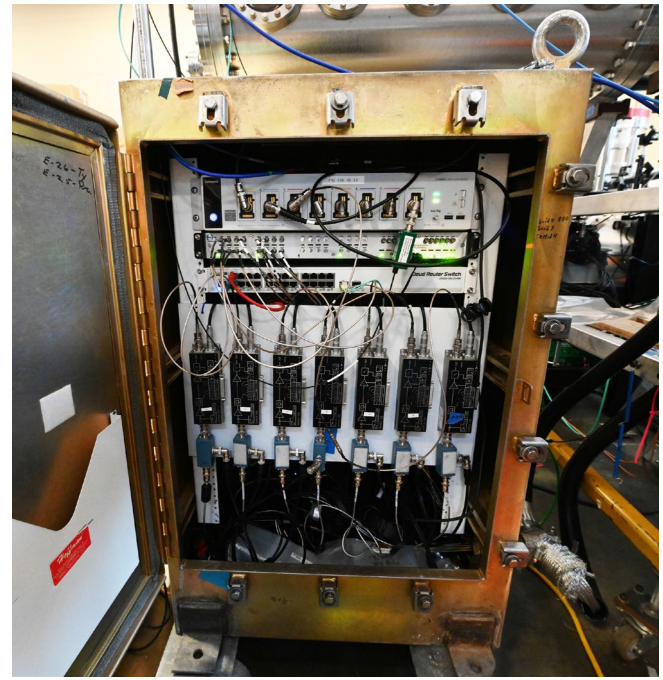
3-4 thin foils are carefully mounted on a brass disk. Then two disks (7 foils total) are stacked in a light-tight, but vented, fashion, in front of the diode housing

Two sets of 7-channel filtered-foil x-ray diodes give time histories of x-ray emission from the plasma (and walls). The 0.2 mm square diodes are fast and have noise levels of ~ 30 nA. They were originally calibrated at Brookhaven synchrotron light source*. Femto preamps convert the tiny currents into a voltage (typical gain of 10^6 V/A), inside an electrically shielded and isolated Hoffman box to local digitizers. Ratios of filtered signals give us electron temperature estimates (> 1keV), assuming bremsstrahlung emission from the plasma.

* G. C. Idzorek and R. J. Bartlett, "Silicon photodiode characteristics from 1 eV to 10 keV", LA-UR-97-2284, SPIE Optical Science, Engineering and Instrumentation Conference, July 27, 1997, San Diego

Small XUV7 diode signals require serious noise reduction measures

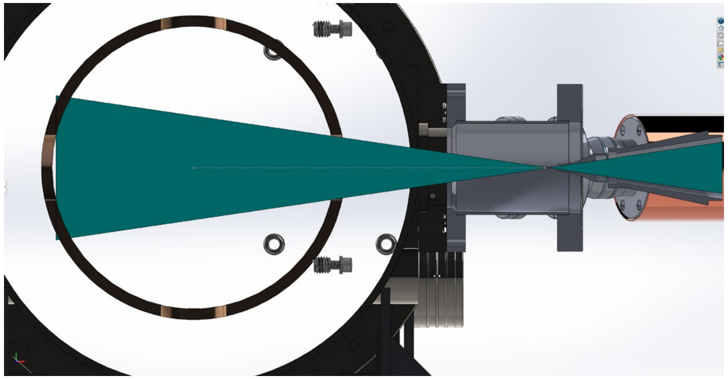
- Isolated UPS power
- Air disconnect for AC line & ground.
- Fiber optic communications
- Ferrite cores (everywhere!)
- Heavy Hoffman shielding enclosure
- Cutoff tubes and secondary metal braids for input cables
- Co-located digitizer…no long cable runs
- No plasma contact to the in-vacuum diodes (otherwise they can act like probes). Using a 23 micron thin mylar prefilter, and bypass vacuum lines so that foils don't break during pump-out.

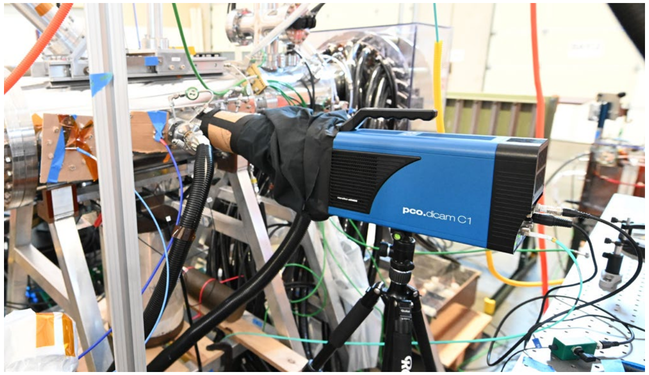


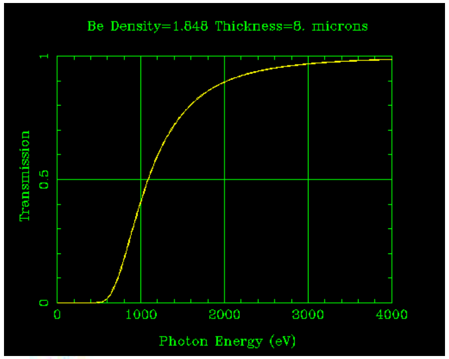
The Hoffman shielding box contains two UPS units, -45 volt bias batteries, bias tees, Femto DHPCA-100 variable gain high-speed current amplifiers, and digitizers over fiber-optic ethernet. Sufficient for 14 channels. Location near FuZe minimizes the cable length before the signals get amplified.

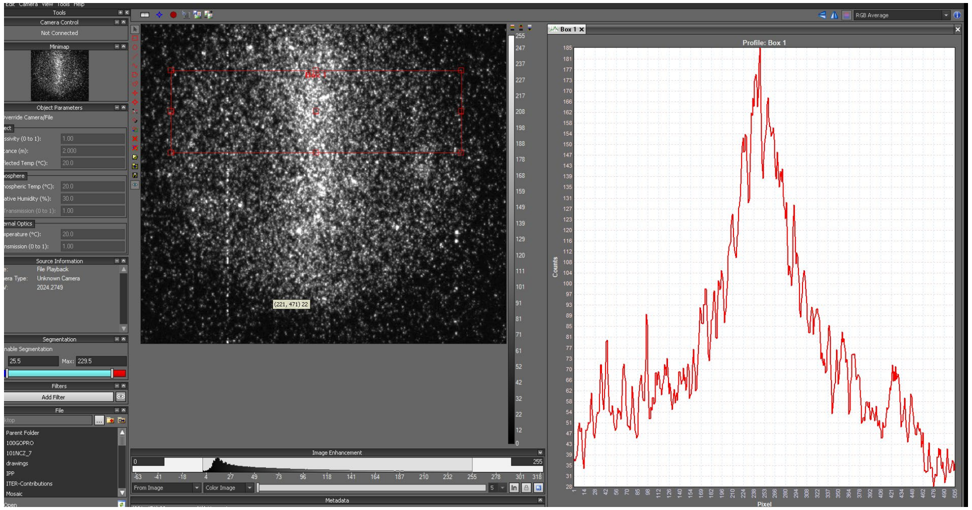
Pinhole soft x-ray Imager

We installed a pinhole imaging cone, with a 2 mm diameter pinhole, an 8 um thin Beryllium filter, and a P47 coated phosphor screen in vacuum, on the inside of a 4.5" Conflat window. A very sensitive PCO C1 camera then acquires a time-gated, intensified image.







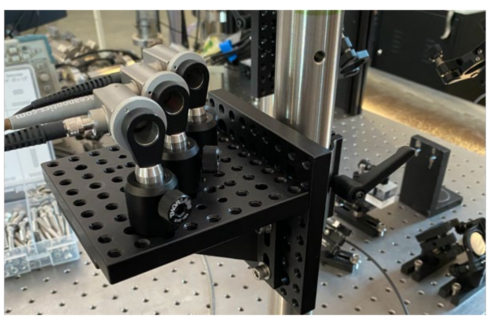


Shot 220405028

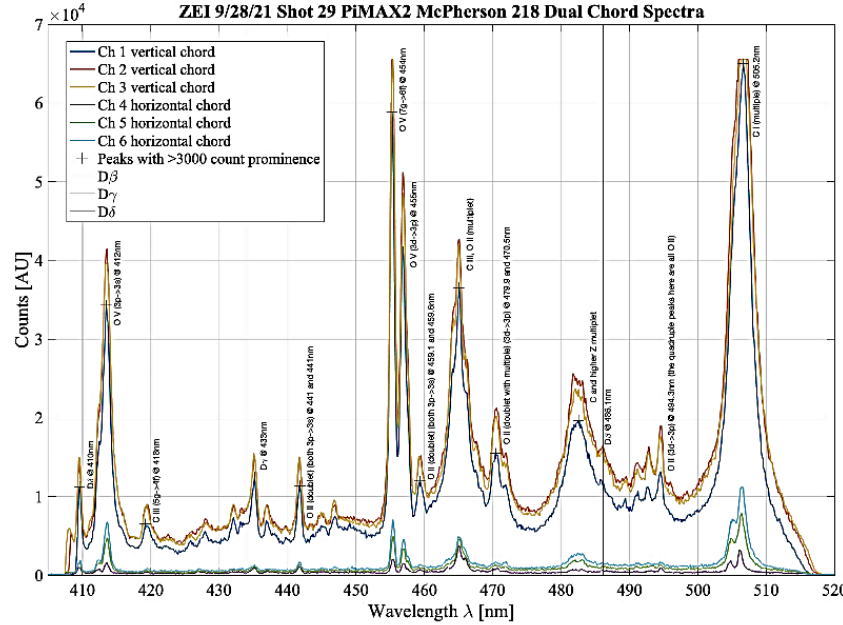
X-Ray Image, lineout of plasma column with FWHM ~ 1.3 cm, near time of peak x-ray emission seen by XUV7 detectors. (Oriented vertically for software purposes). We plan on improving the S/N by switching to a more efficient phosphor.

“Hydra”: A six-channel fiber-coupled McPherson 218 visible Spectrometer with PiMax-2 intensified gated camera

Intensified PiMax 256 x1024 pixel snapshot camera is mounted on the output of the McPherson 218 spectrometer. The fiber harness and collimators are laying on top of the instrument.

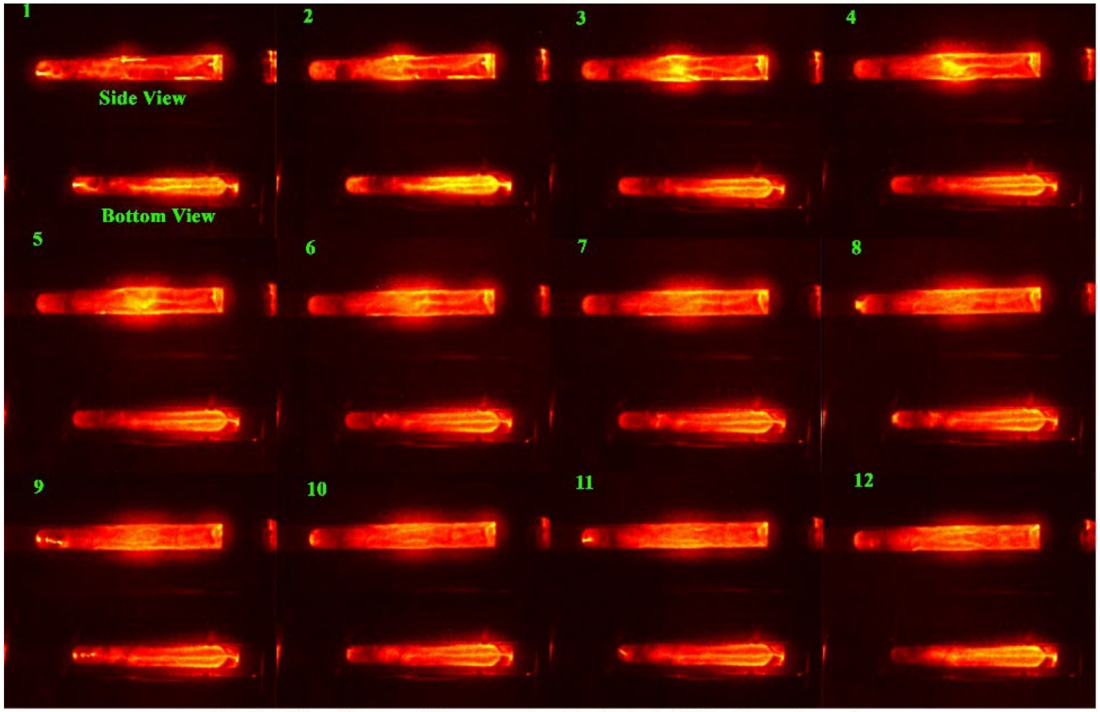


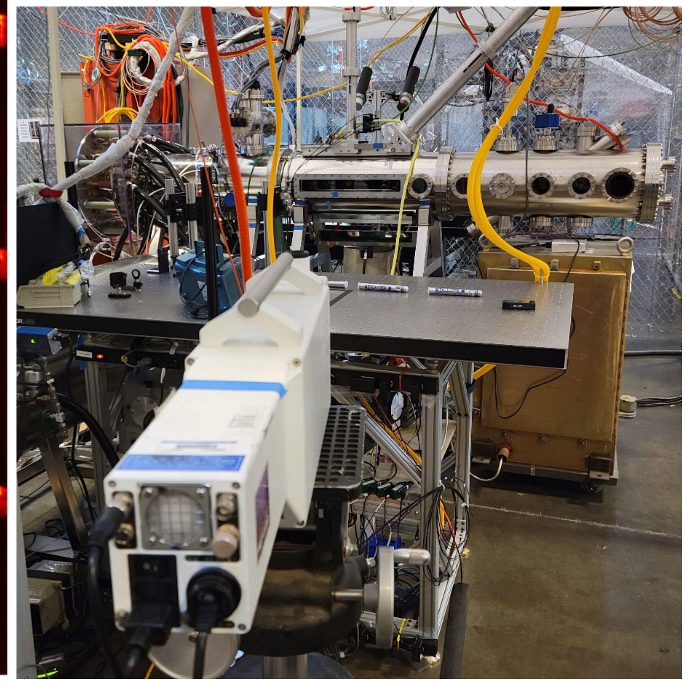
Here, a bracket holds three of the metal off-axis parabolic collimators, which can be aimed through any window on FuZe. They feed light on fibers to the spectrometer input slit.



The Hydra diagnostic has enabled us to see direct evidence of the plasma lighting up our quartz windows (silicon and oxygen lines), as well as carbon impurities from the electrodes, from six different views during a single discharge. In this case, three sight lines on top, and three on a side view are plotted, with 100 nm of spectral coverage. High density continuum and Stark broadening are often present.

Hadland 200 Million frame/second fast camera



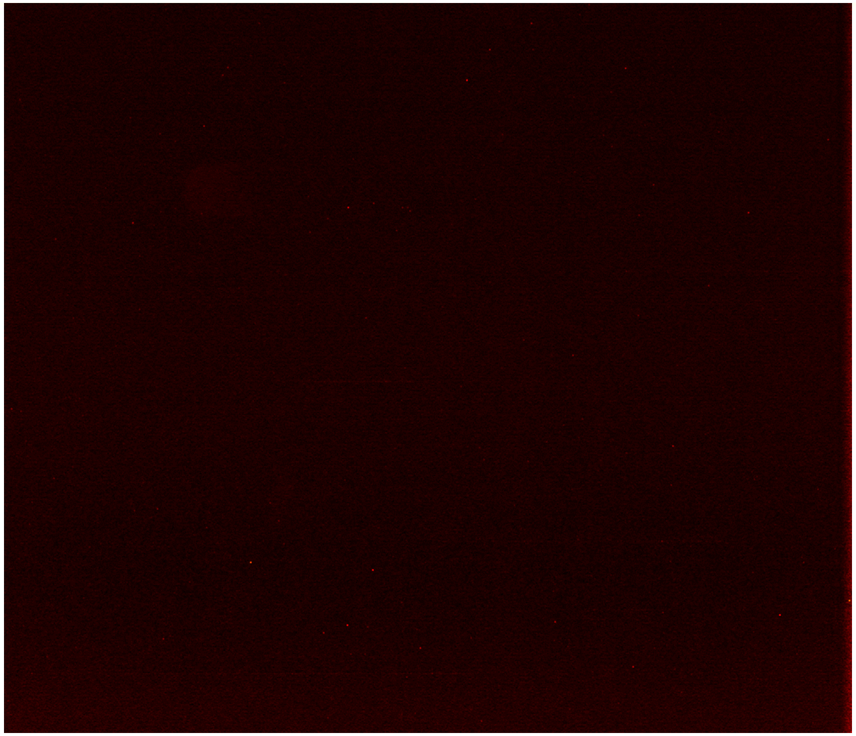


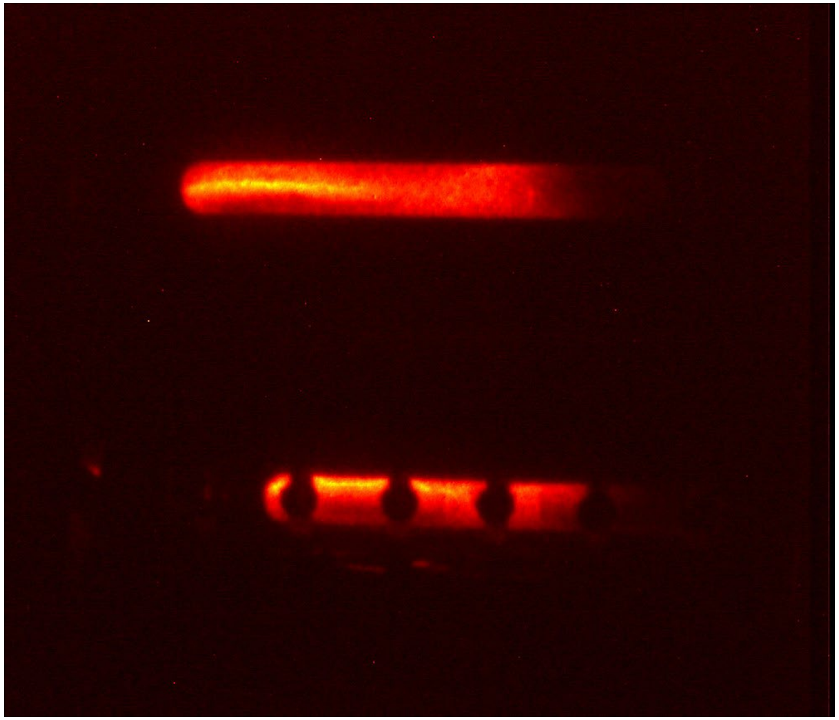
Hadland Fast Camera 12-frame movie, white light, 3 Million frames/second, each with 20 nanosecond exposure time, covering from 18 to 22 microseconds

Our Hadland camera is a versatile tool for observing visible light from the plasma, to study formation and symmetry of the pinch over time in a single shot. Long windows on the side and bottom of the experiment are viewed simultaneously (directly on the side, and with a 45 degree mirror at the bottom) through slots in the outer electrode.

There are two distinct phases of pinch evolution:

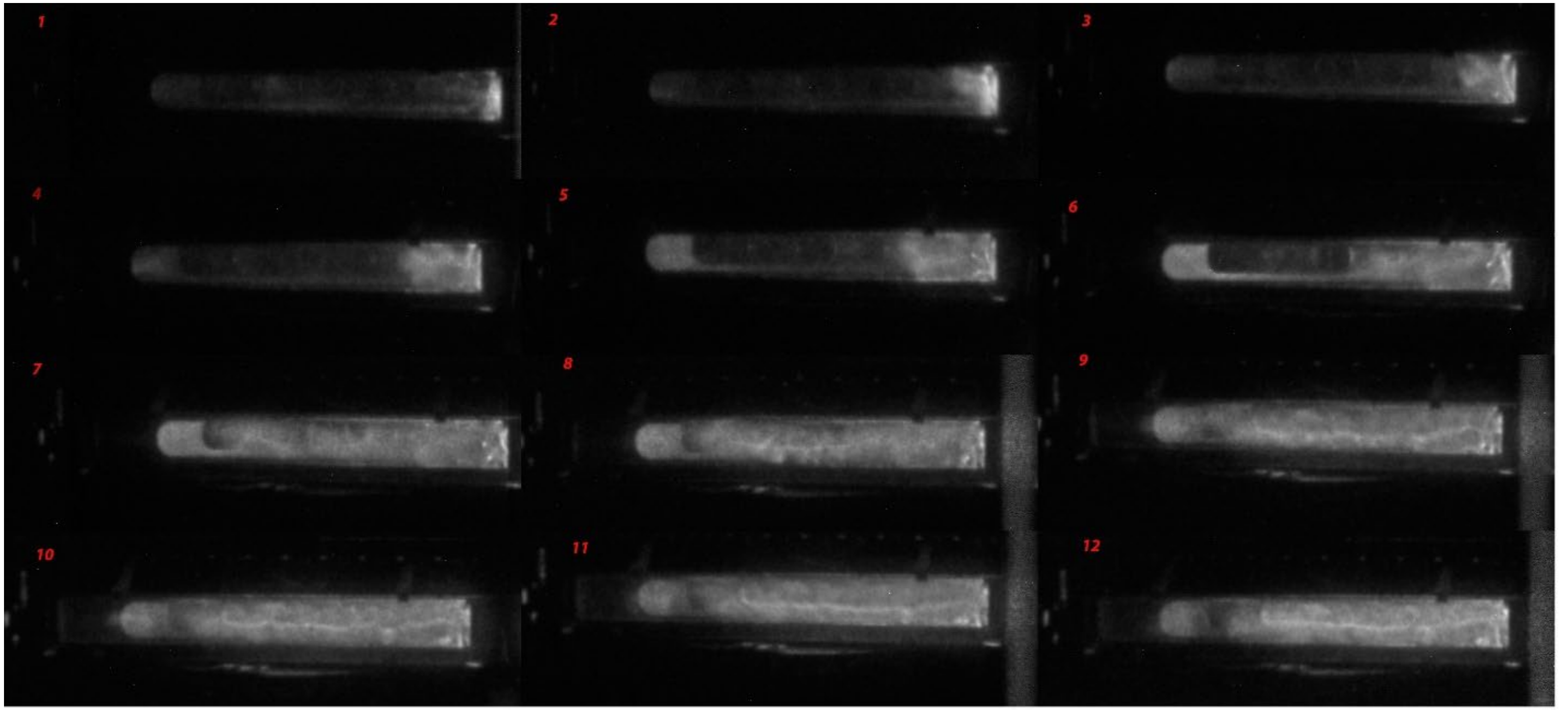
1) Flow from the nose cone towards end electrode





At first we see plasma flowing from left to right (from the plasma gun & nose cone towards end electrode 0.5 meters downstream). The upper image is the side view, while the lower image is from the bottom of the machine. The five dark circular objects are Hydra light collimators mounted on the bottom window. This phase is "wiggly", and is centered within the outer electrode region. As the bank voltage is increased, it occurs earlier in time. Or as the gas puff pressure is increased, it occurs later in time. Shot 220304011, at 14 kV bank voltage, with Hadland starting at 13 usec, frame rate of 1 MHz, and 500ns exposures.

There are two distinct phases of pinch evolution:
2) End electrode towards the nosecone



Then there is a backwards phase (right to left) from the end wall position back towards the nosecone (seen in the Hadland frames above, Shot 220127050, starting at 20 usec, 4 MHz frame rate, 35 nanosecond exposures). Interactions are often seen at the window surface in this phase, or on port edges. Neutrons and x-rays are seen during the backwards phase, as well as visible light emission out near the long viewing windows.

Three Rhodium Neutron activation counters*

- Thermal neutron capture in a thin 8-gram Rhodium foil (surrounding a Geiger tube, which itself is surrounded by a polyethylene moderator and cadmium shielding) activates to ^{104}Rh which decays with a 2.44 MeV beta in a 42-second half life. Readout with NIM electronics. The cadmium prevents background thermal neutrons from being detected. The moderator converts the fast DD neutrons.
- A 60-second counting window begins after the plasma pulse is over. Calibration is ~ 10^5 neutrons at the plasma centerline, per count, and backgrounds are ~20-30 counts.

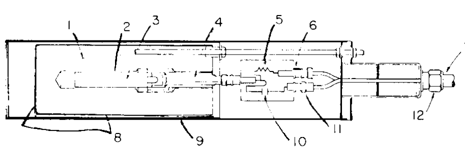
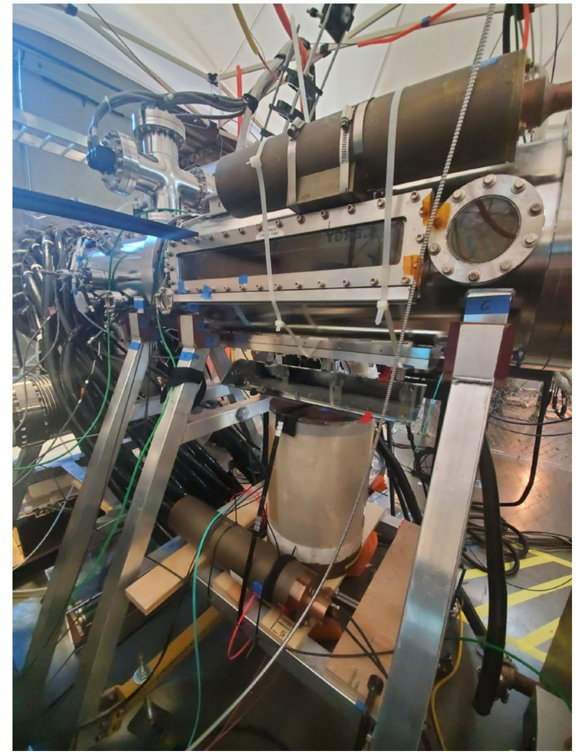


FIG. 5. Rh-activation neutron yield detector. (1)—Polyethylene moderator block, (2)—7.5-cm-long, 0.25-mm-thick Rh foil, wrapped on sidewall of (3)—Victoreen 1B-85 thyrode, (4)—high-voltage connector, (5)—10-kΩ ballast resistor, (6)—SHV high-voltage coaxial connector, (7)—Cu tubing conduit, (8)—0.5-mm-thick Cd sheet, (9)—Brass tubing outer shell, (10)—0.1-μF blocking capacitor, (11)—BNC coaxial signal connector, (12)—"Swagelok" pipe fitting.

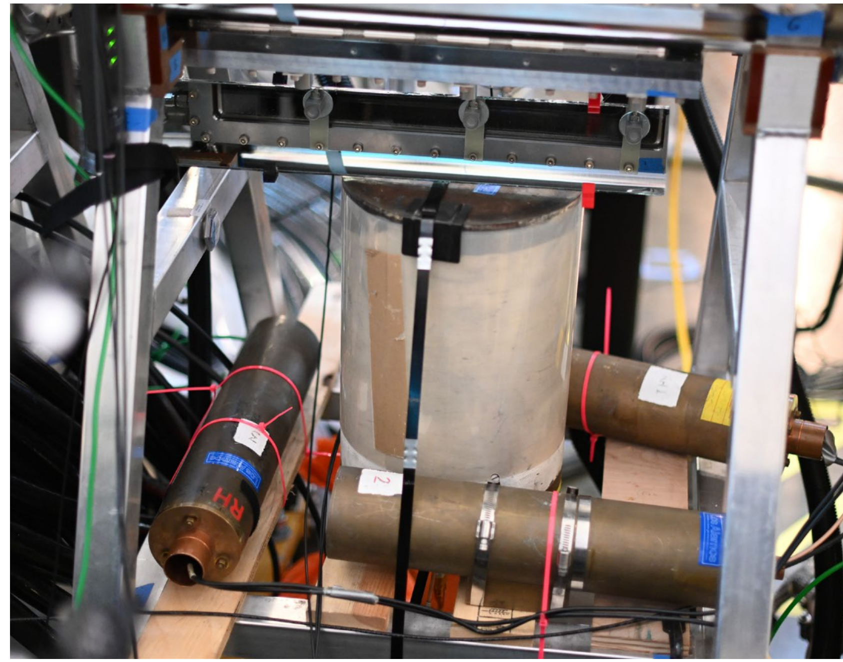


Two Rhodium (brass cylinders) neutron activation detectors are visible in this image, placed at various locations near FuZe

* C. A. Ekdahl, "Neutron diagnostics for pulsed high-density thermonuclear plasmas", Rev Sci Inst, **50**, 941 (1979)

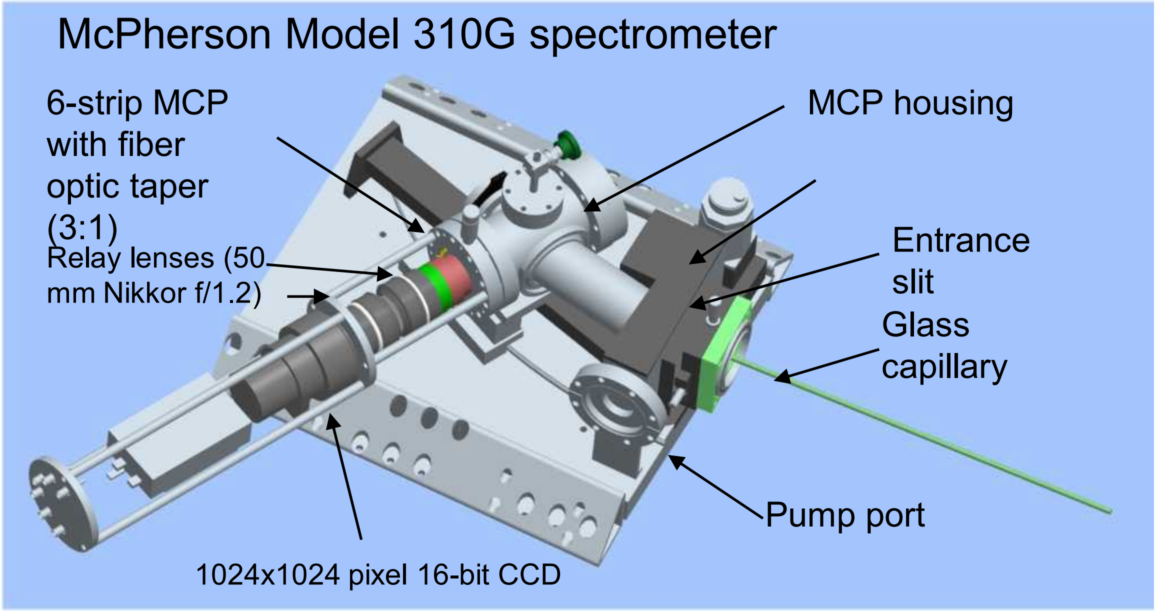
Arsenic Neutron Activation Detector

- We have also deployed an arsenic (8kg of As powder embedded into plastic) neutron activation counter, built by Sandia
- Eddy Jacobs, US Patent 4,271,361 July 2,1981, “Arsenic Activation Neutron Detector” Sandia National Laboratory
- E. L. Jacobs, S. D. Bonaparte, P. D. Thacher, “An arsenic-activation detector for bursts of 2.5 and 14 MeV neutrons” , Nuclear Instruments and Methods In Physics Research, Volume 213, Issue 2, p. 387-392, Aug 1983
- ^{75}As is activated to a metastable state by fast DD neutrons, and has a 17 millisecond half life, emitting a 300 kV gamma. We wait 5 milliseconds for things to cool off, and count pulses with a 5” diameter PMT for 50 milliseconds, producing a count, with an efficiency of ~ 1 count per 2100 neutrons through the scintillator.



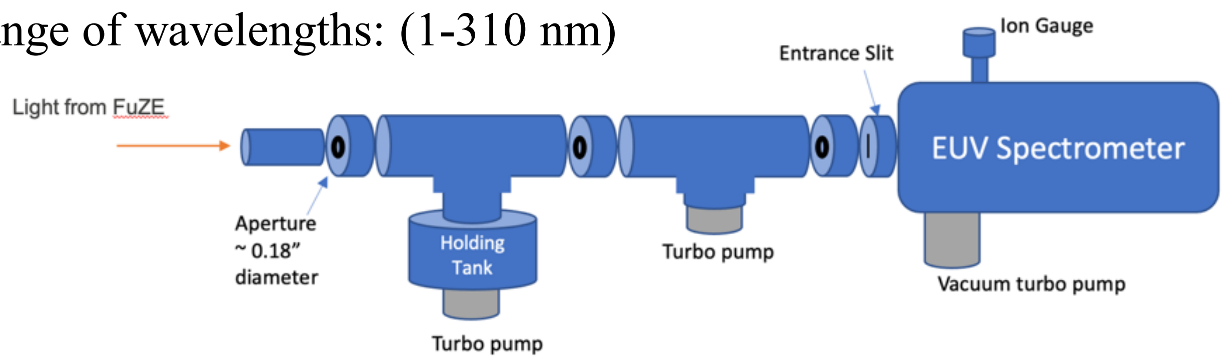
The large (and heavy) Arsenic neutron activation detector, with 8 kg of As powder embedded in plastic, is surrounded by lead and an iron cylindrical case. It is located 30 cm underneath the FuZE centerline. You can also see three Rhodium brass cylindrical detectors lying nearby in this image.

We will install an Extreme Ultraviolet Spectrometer from U of Nevada (Reno)

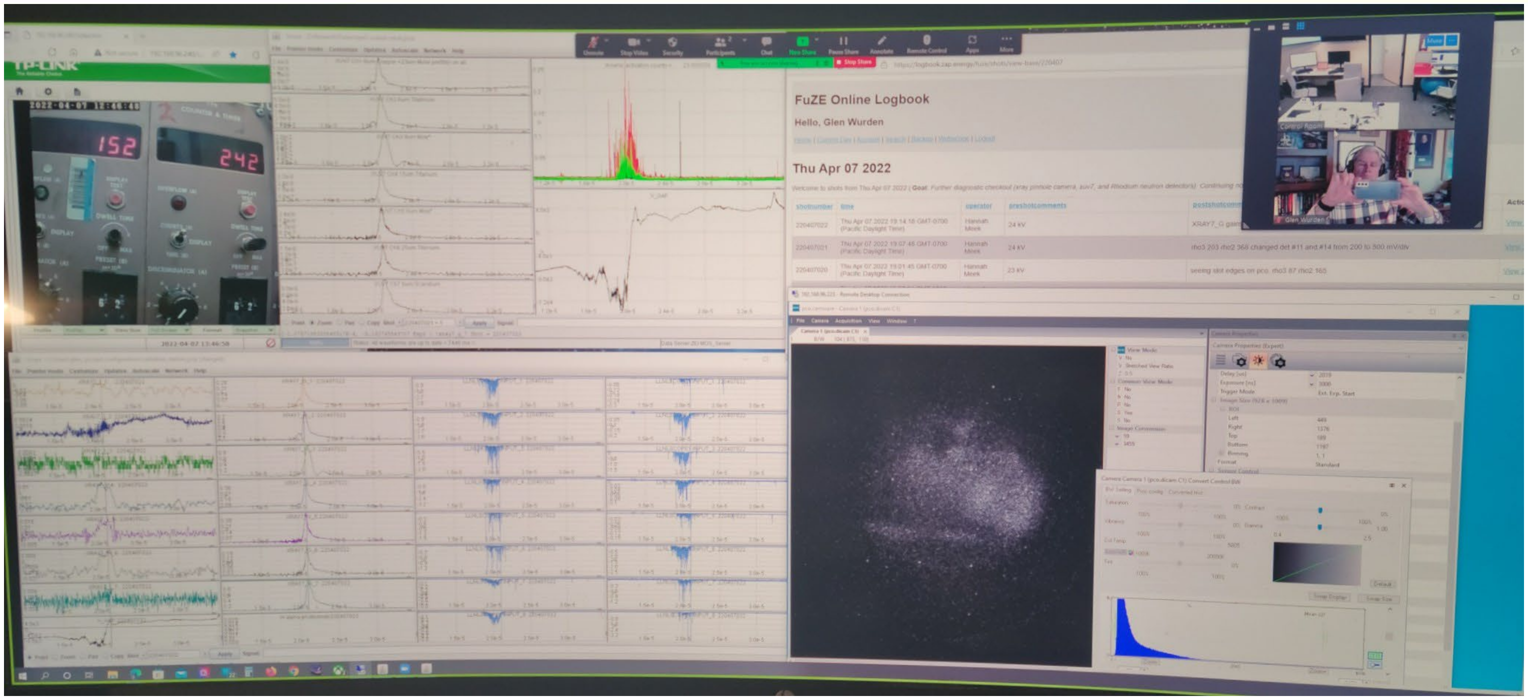


Due to pressure surges from the FuZe gas puffs and late time expanding hot plasma column, differential pumping and multiple apertures are required to allow gated MCP operation at high voltages without arcing. Also, the MCP voltages will be have fast HV pulsing, so that the late arriving gas won't cause arcs in the MCP.

This instrument will produce high-quality spectra over a wide range of wavelengths: (1-310 nm)



A remote presence via Zoom & VPN



Through VPN and a Zoom presence in the control room (not just for meetings, but plasma operations as well) we have been able to participate for many more run days than would have been possible by travelling in person. It has really made a difference in enhancing our collaboration.

What are we learning from these diagnostics?

- Plasma dynamics through visible & x-ray imaging, as a function of gas pressure, puff timing, bank voltages
- Absolute soft x-ray brightness, emission from both plasma and metal edges (electrodes and walls). Estimates of electron temperature via filter ratios, but also observation of non-thermal higher energy x-rays
- Impurity light intensity, timing, and locations, from plasma and near surfaces (carbon, silicon, oxygen)
- Neutron yield, and spatial symmetry
- Complementary with other Zap Energy and LLNL diagnostics (magnetics, density, TS, scintillators)