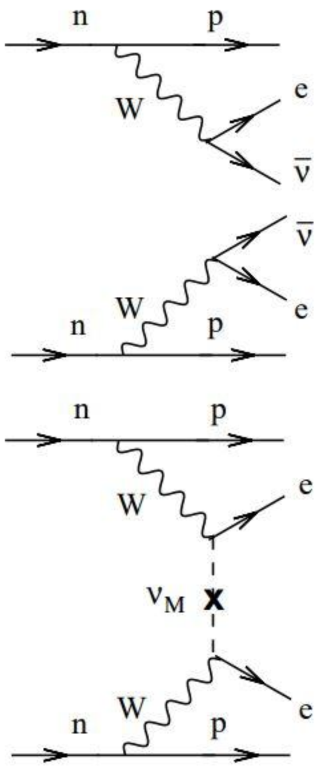
Machine Vision for Video-Based Material Strain Extraction

Sonata Simonaitis-Boyd, Alexander Leder, Aobo Li

A3D3 All-Hands Meeting / August 16th, 2025

Finding Majorana: Neutrinoless Double-Beta Decay

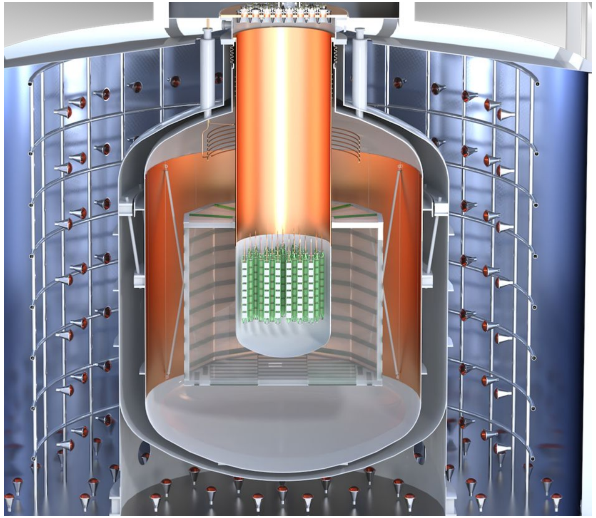
- big question: is the neutrino its own antiparticle (Majorana particle)?
- SM-allowed process: 2v□□ decay
  - rare process (occurs in e.g. ^{76}Ge, ^{136}Xe, ^{130}Te)
  - decay energy split between antineutrinos and electrons
- BSM process: 0v□□ decay
  - would confirm neutrino is Majorana
  - electrons carry away all decay energy
- large experiments focused on search for 0v□□: MAJORANA DEMONSTRATOR, LEGEND, nEXO, KamLAND-Zen



Scaling Up: From 200 to 1000

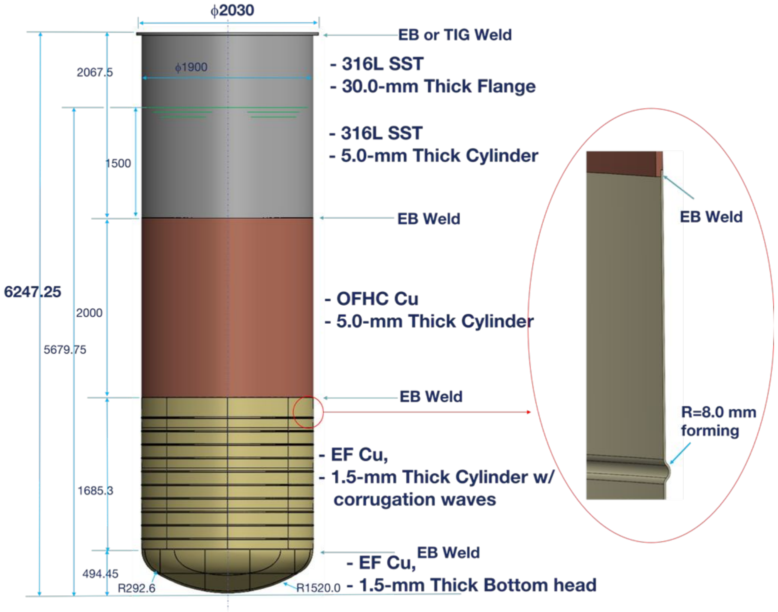
- [Large Enriched Germanium Experiment for Neutrinoless □□ Decay (LEGEND)]
- LEGEND-1000 will succeed in-operation LEGEND-200, increasing sensitivity of 0v□□ decay searches
  - L200 latest results (in review): arxiv.org/abs/2505.10440
- L1000 will operate ~1 ton enriched Ge detectors immersed in 200+ tons liquid argon (LAr), with goal of obtaining 0v□□ half-life lower limit of 10^{28} yr
- ultra-low background levels in cryostat require high radiopurity for both structural materials and LAr
- hybrid approach: underground LAr (UGLAr) + atmospheric LAr (ATLAr) to balance cost and need for low backgrounds

LEGEND Large Enriched Germanium Experiment for Neutrinoless ββ Decay



Split the Difference: the Reentrant Tube

- will serve to separate high-purity UGLAr from lower-purity ATLAr
- reentrant tube itself must meet several requirements:
    - radiopurity of tube materials
        - oxygen-free high-conductivity (OFHC) copper
    - tube must maintain structural integrity over experiment lifetime
        - only a few mm thick at narrowest point
    - tube must withstand cryogenic conditions (87 K) without degradation
    - tube must be leak-tight to prevent LAr cross-contamination

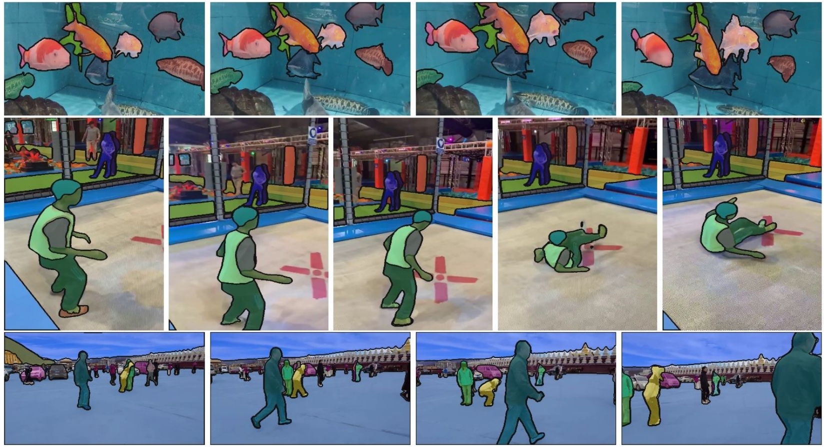


Totally Tubular: LoFi Cylinder Testing

- small-scale reentrant tube prototypes: “LoFi cylinders” of commercially available high-purity OFHC copper
- testing objectives:
  - determine cylinder burst pressure
  - measure strain vs pressure at critical weld locations
  - evaluate cylinder burst performance reproducibility
- each cylinder outfitted with three 2D strain gauges; regular probing of strain gauge data, pressure data
- **strain gauge data difficult to interpret, does not correlate with pressure data, and video footage shows gauges separating from cylinder during testing**
  - of the four tests conducted, video footage of only two is available

Sam I Am: Meta's Segment Anything Model 2 (SAM2)

- transformer-based, Python-based, pre-trained computer vision model
- handles videos by analyzing individual frames and propagating masks
- intuitive prompting, with easy-to-follow example notebooks
  - video prediction notebook forms basis of analysis pipeline



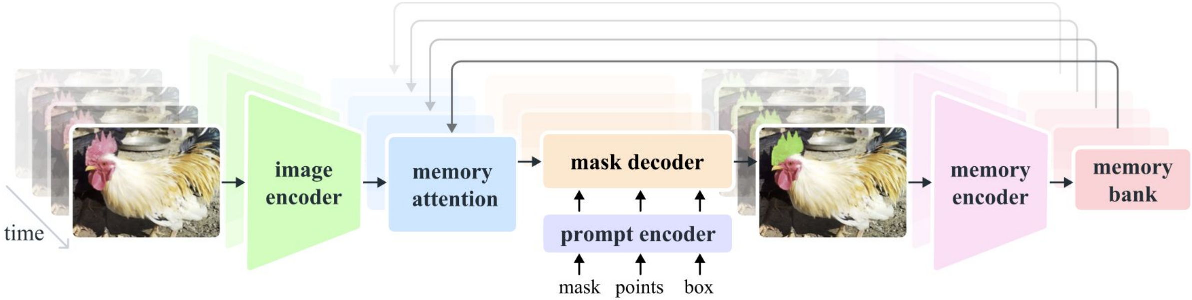
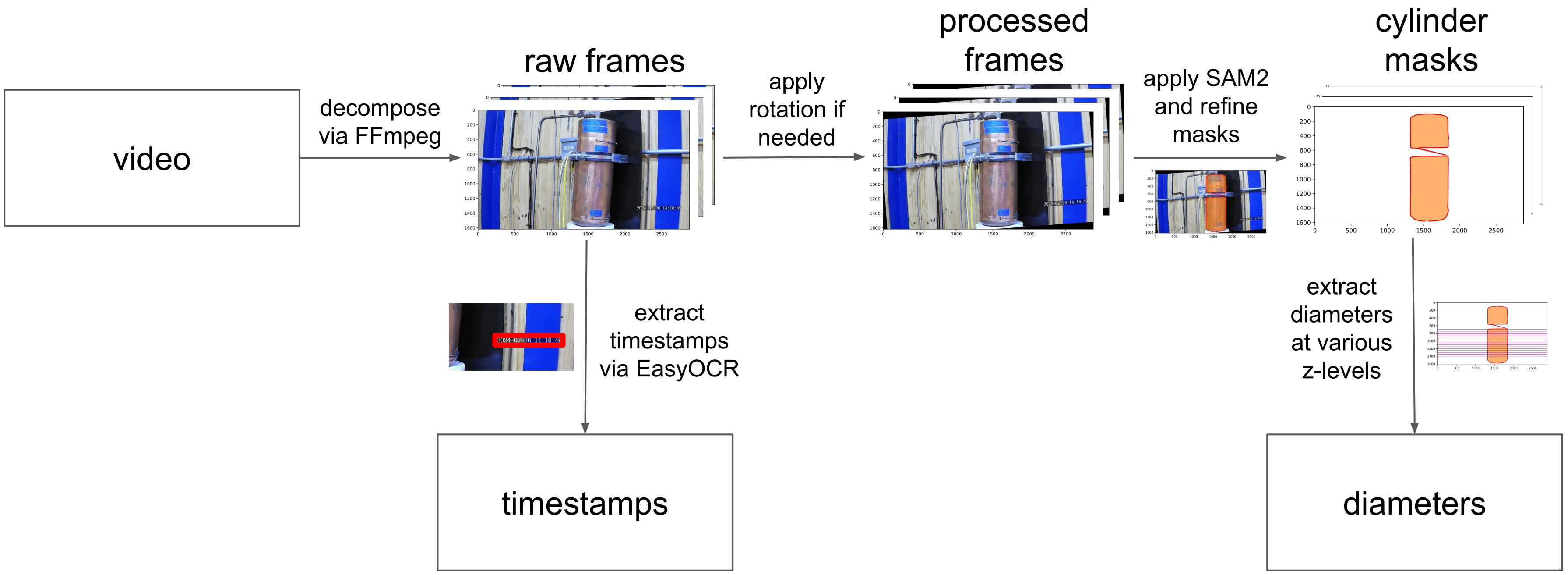


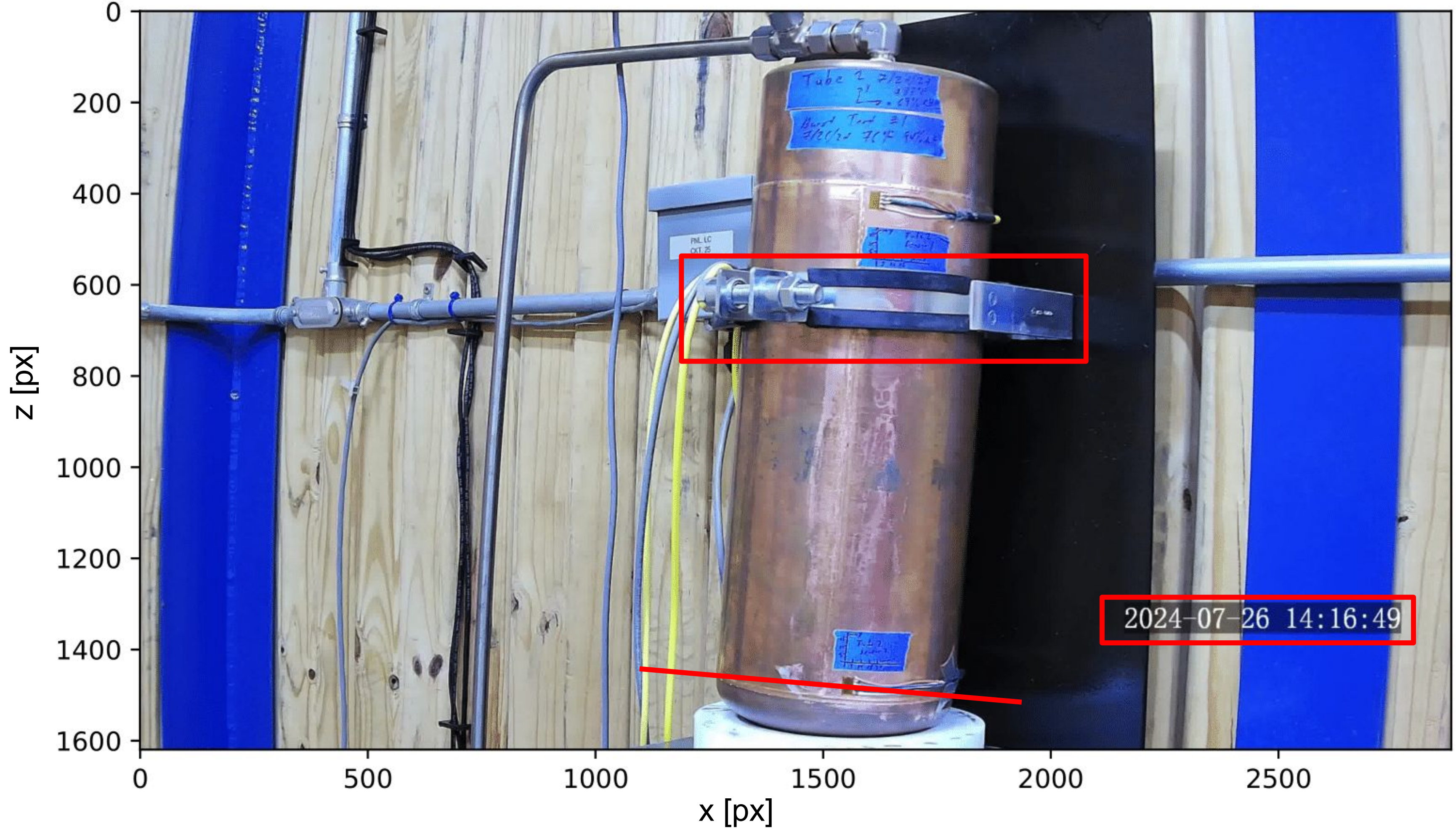
Image credits: SAM2 on Github

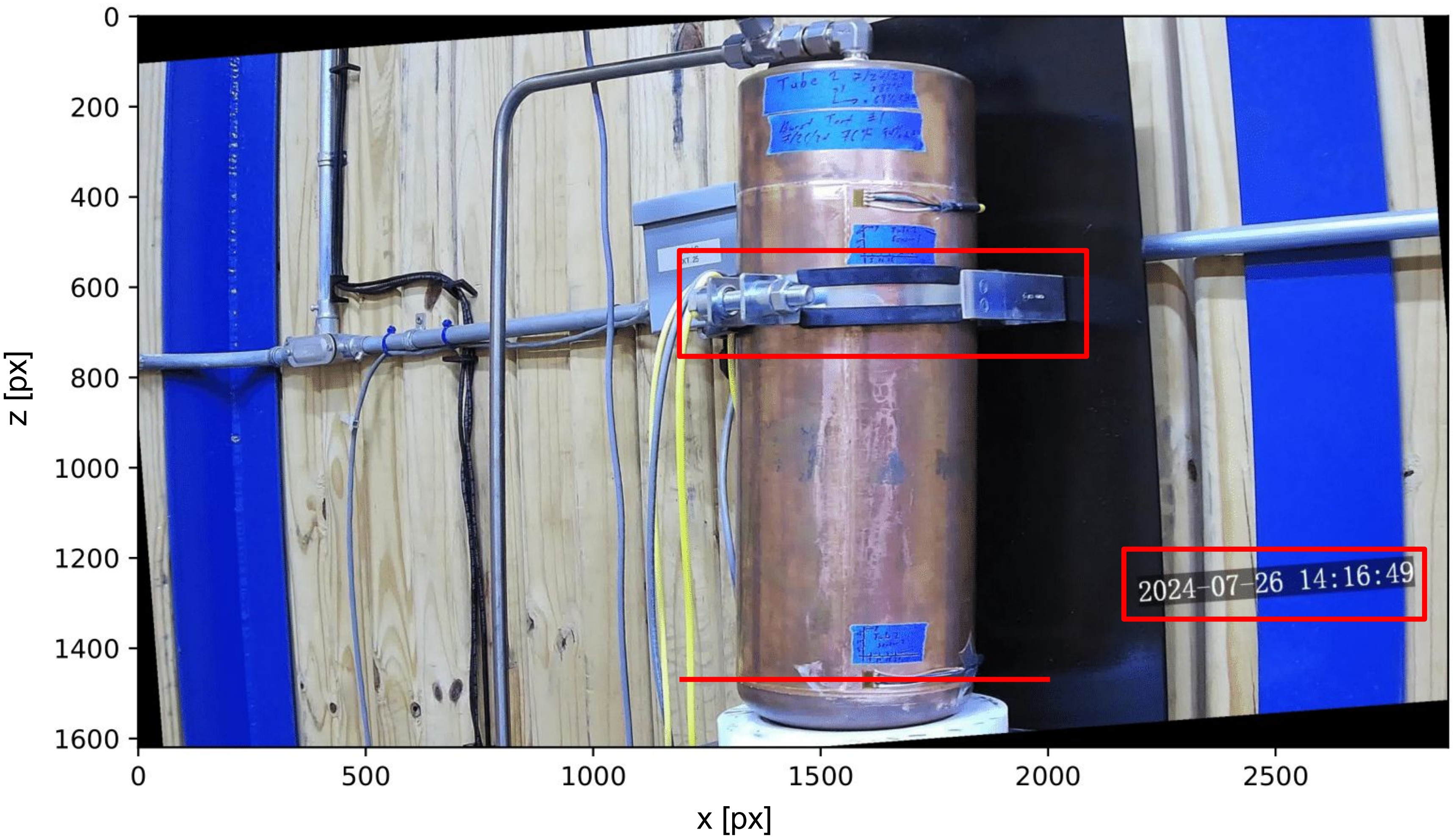
Gimme Gimme Gimme: CV for Data Extraction

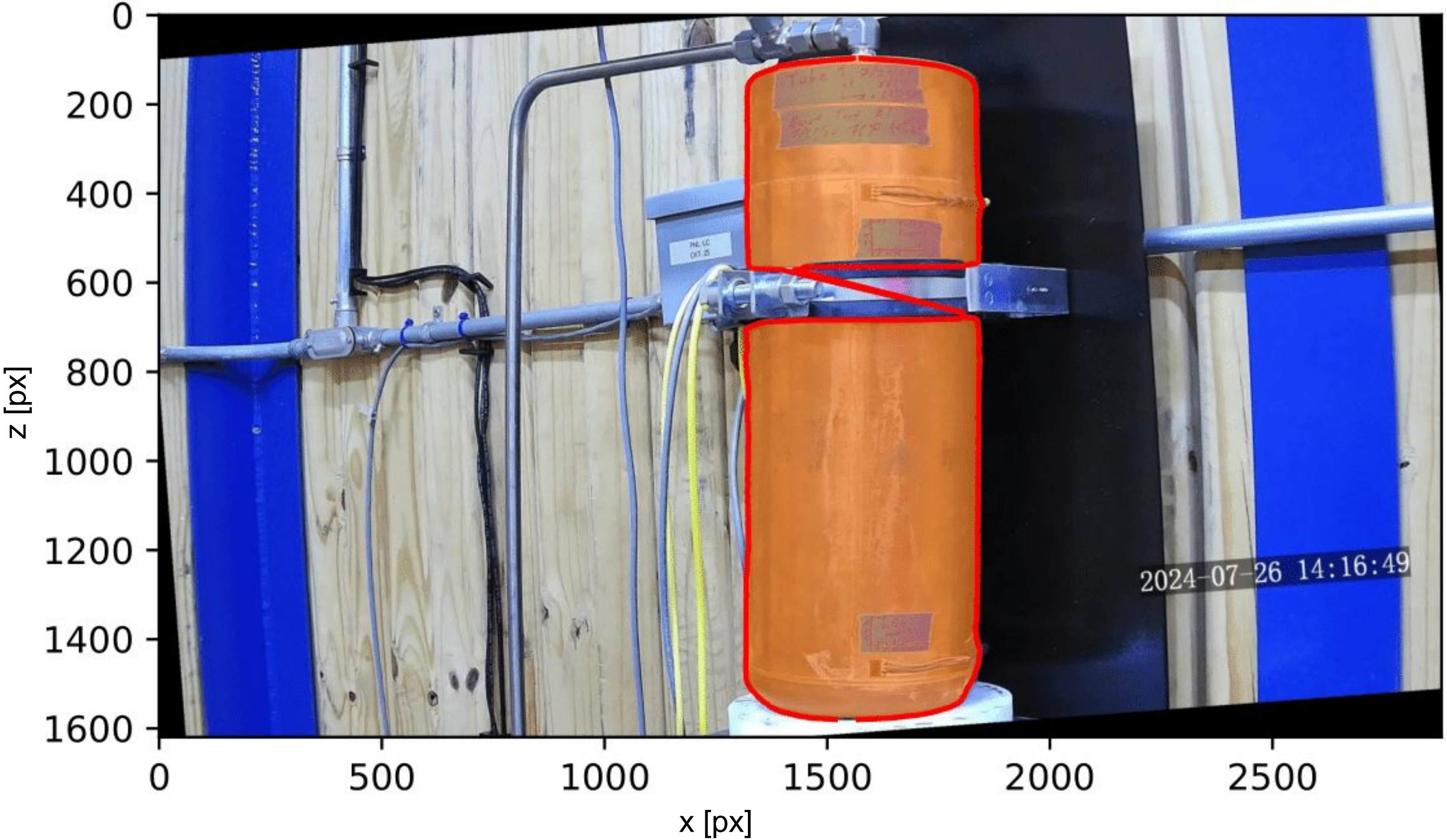
- test footage decomposed into individual frames using FFmpeg
- rotational offset applied as necessary
- SAM2 for object segmentation
  - refine cylinder masks
  - extract diameter measurements at various z-levels
  - repeat for all frames
- to synchronize pressure and diameter data, used optical character recognition software EasyOCR to extract timestamps from frames
- technical issues: dead frames, obstructing elements in video, timestamp contrast with background

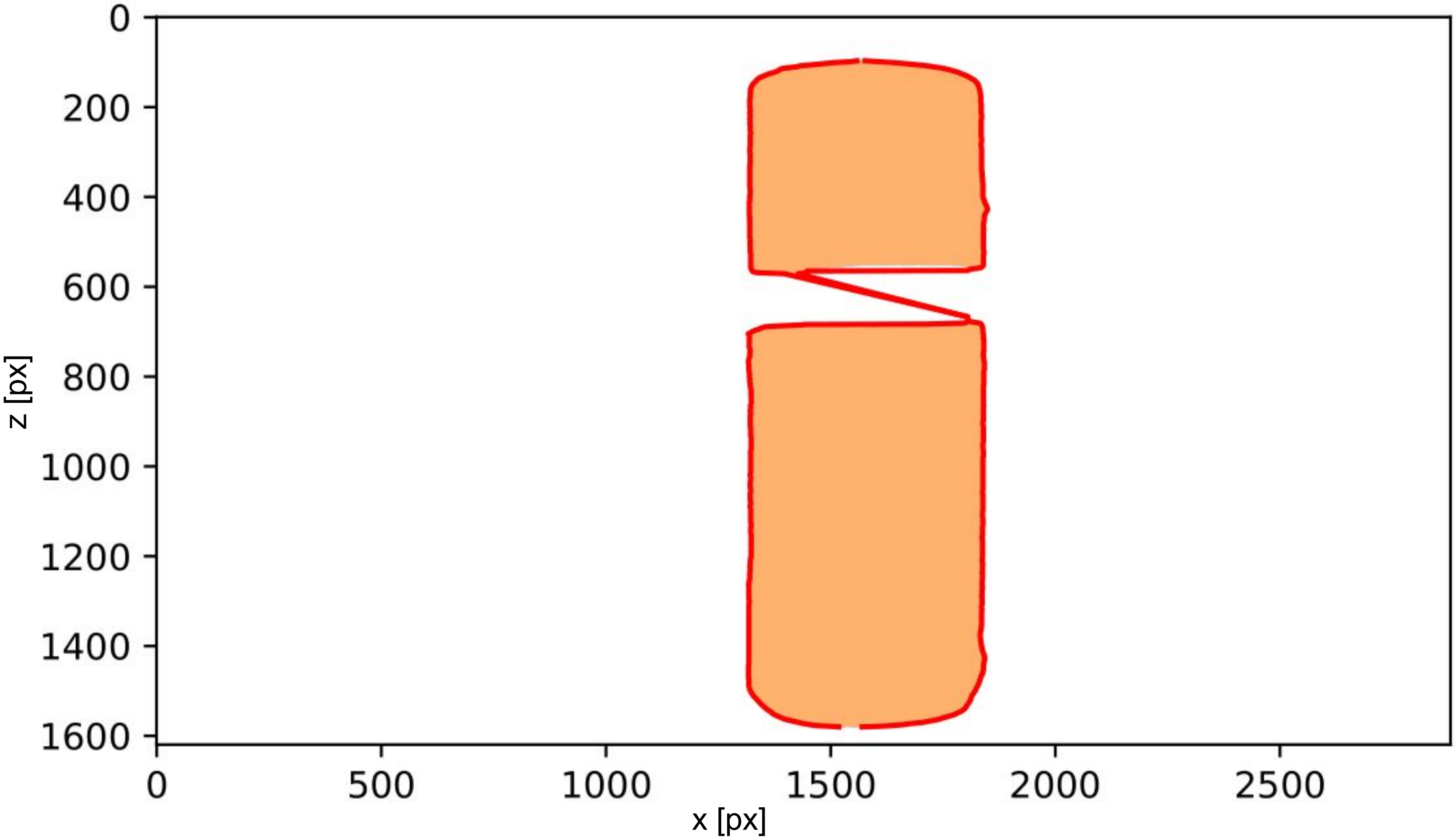
Gimme Gimme Gimme 2: Analysis Pipeline Boogaloo

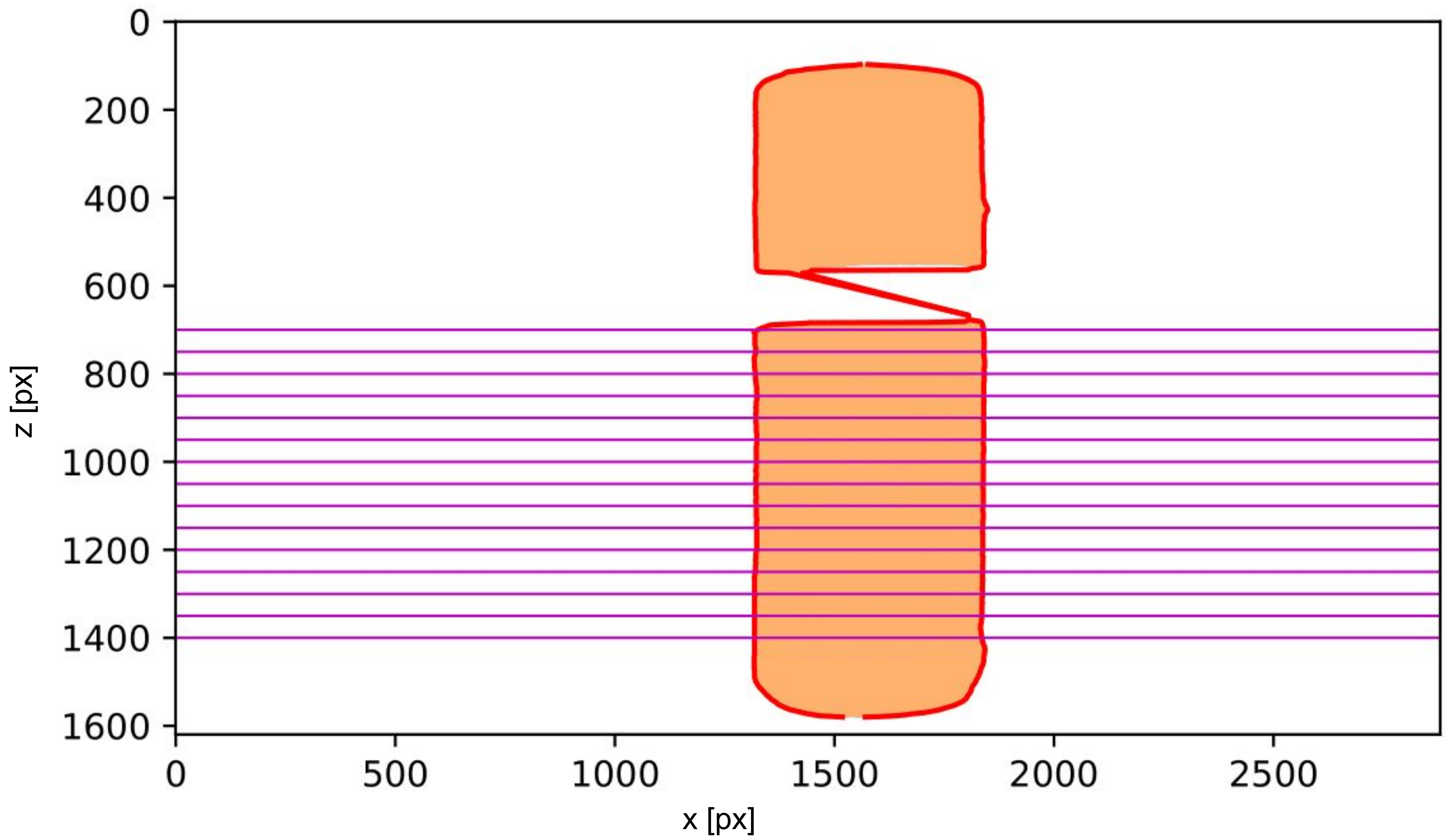



0
200
400
600
800
1000
1200
1400
1600
z [px]
0
500
1000
1500
2000
2500
x [px]
Tube 2
PNL LC
CKT 25
2024-07-26 14:16:49

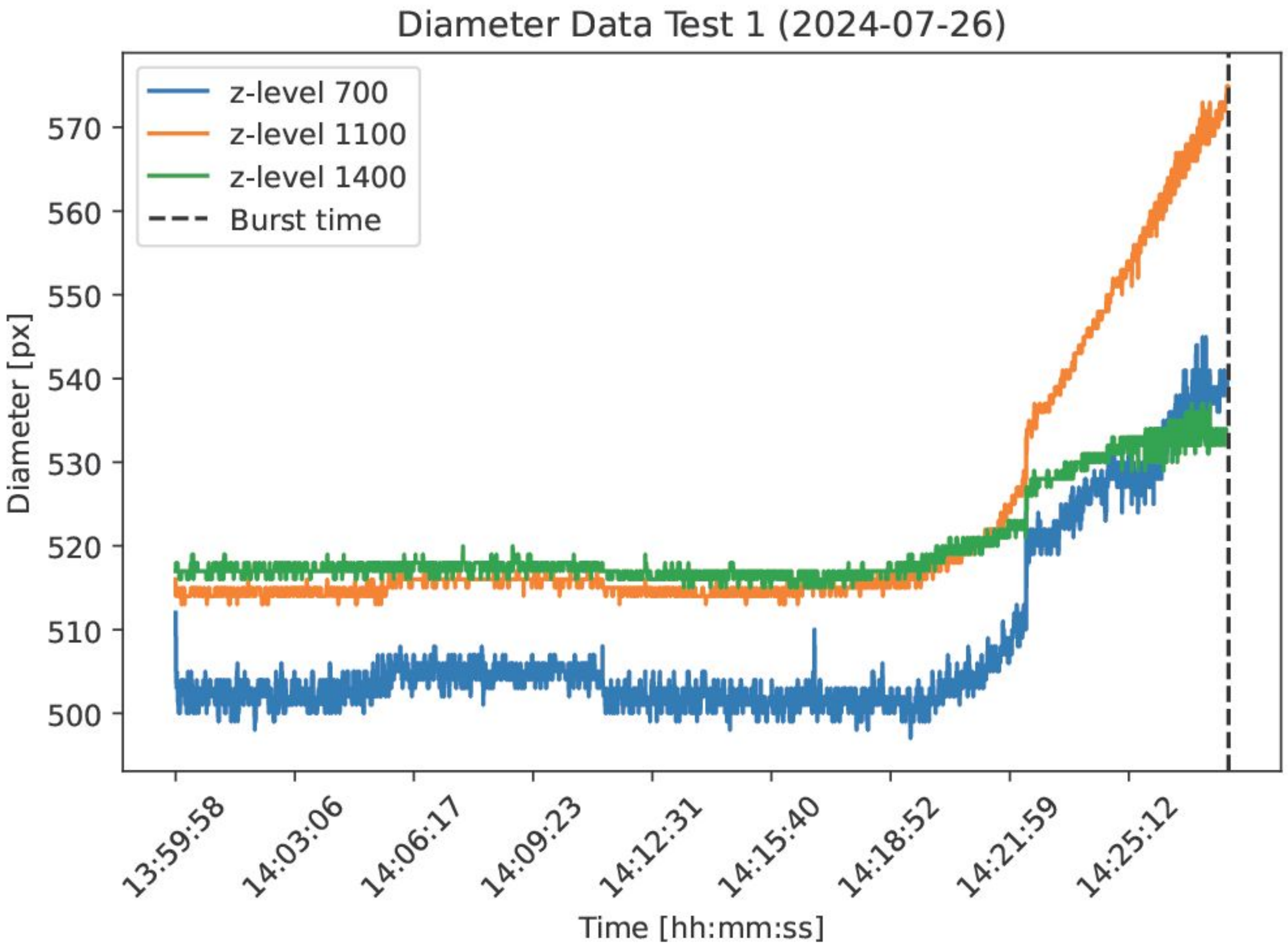

2024-07-26 14:16:49
z [px]
0
200
400
600
800
1000
1200
1400
1600
0
500
1000
1500
2000
2500
x [px]

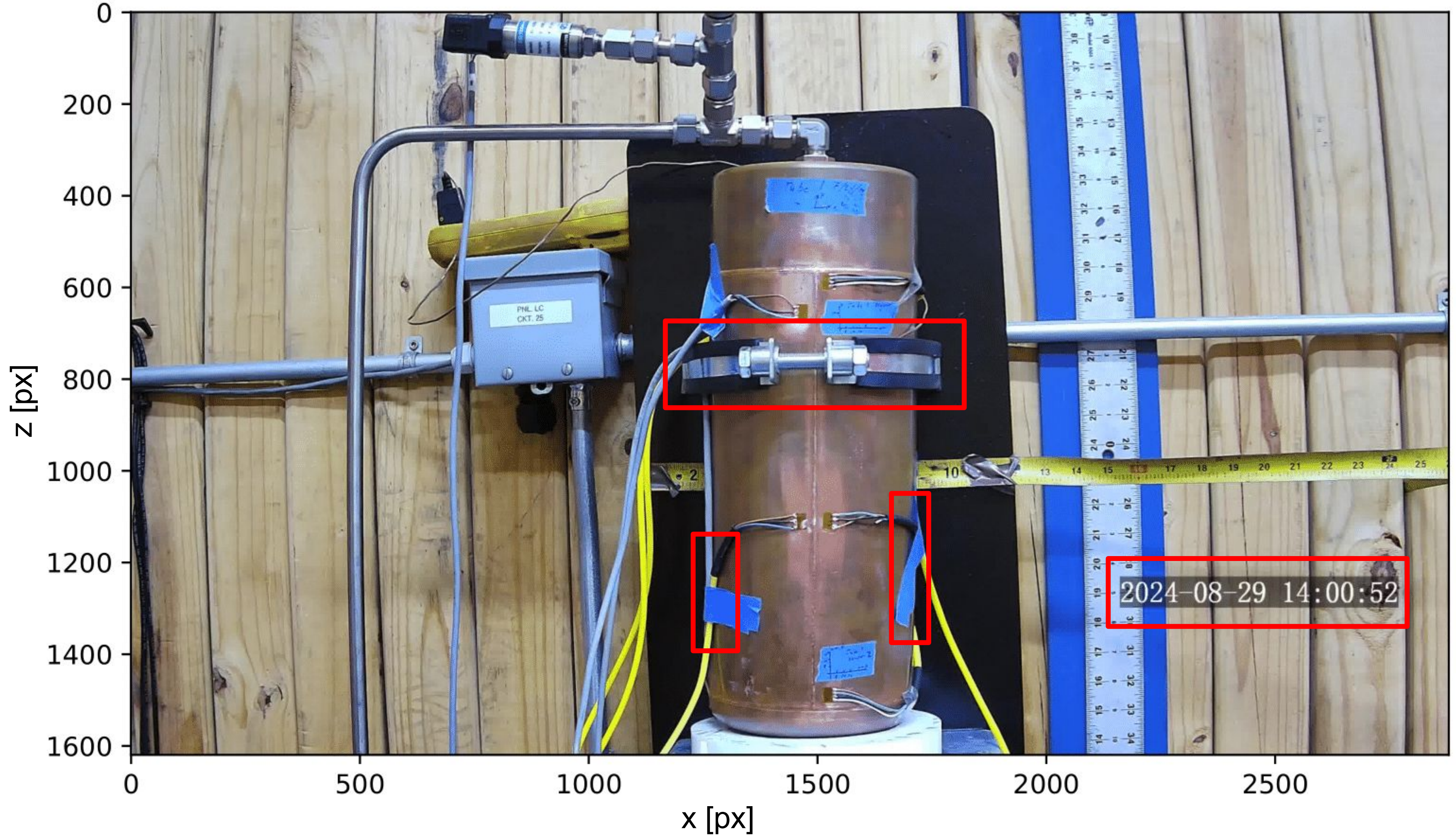

z [px]
x [px]
0
200
400
600
800
1000
1200
1400
1600
0
500
1000
1500
2000
2500
2024-07-26 14:16:49


0
200
400
600
800
1000
1200
1400
1600
z [px]
0
500
1000
1500
2000
2500
x [px]

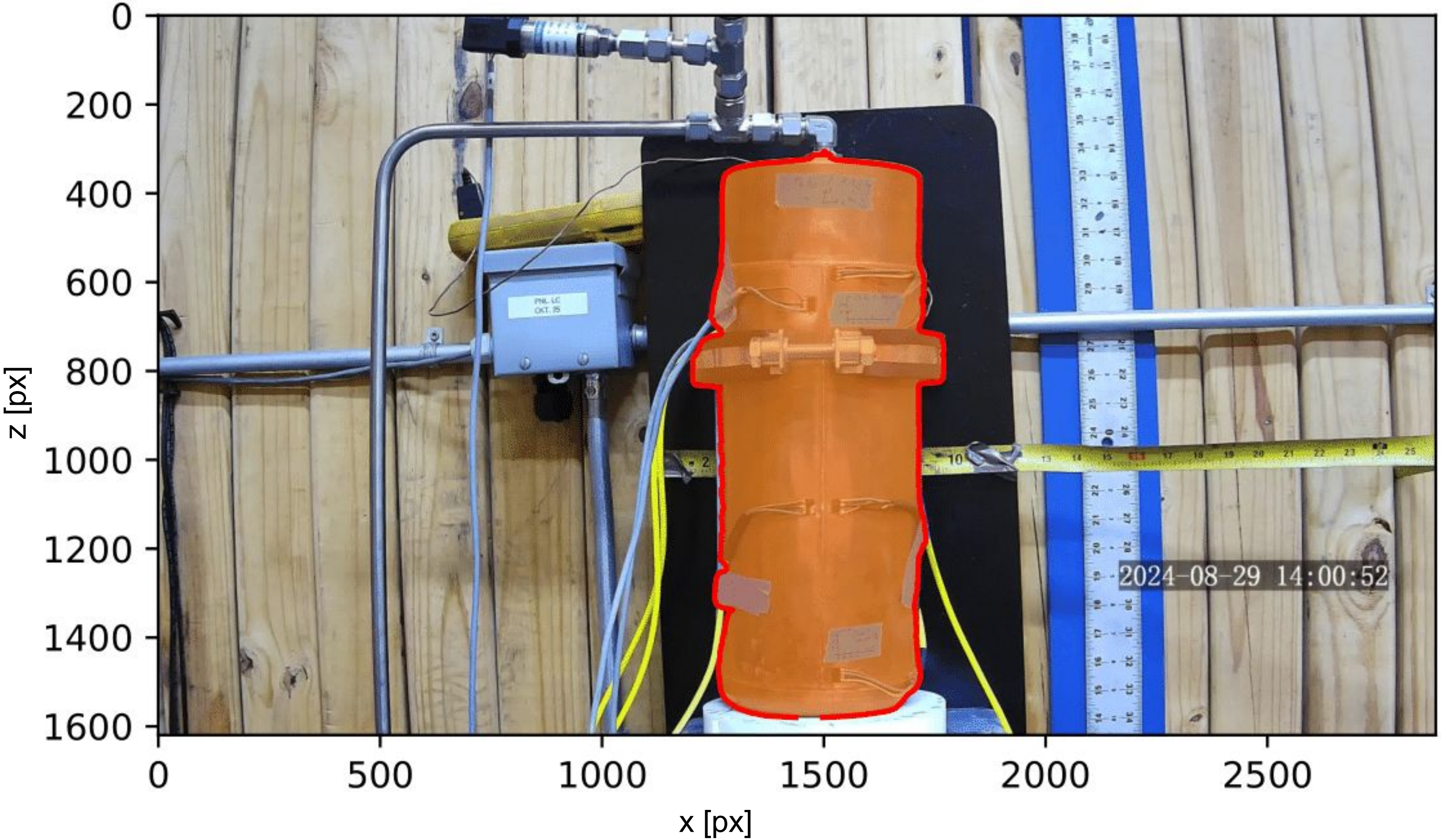


0
200
400
600
800
1000
1200
1400
1600
z [px]
0
500
1000
1500
2000
2500
x [px]

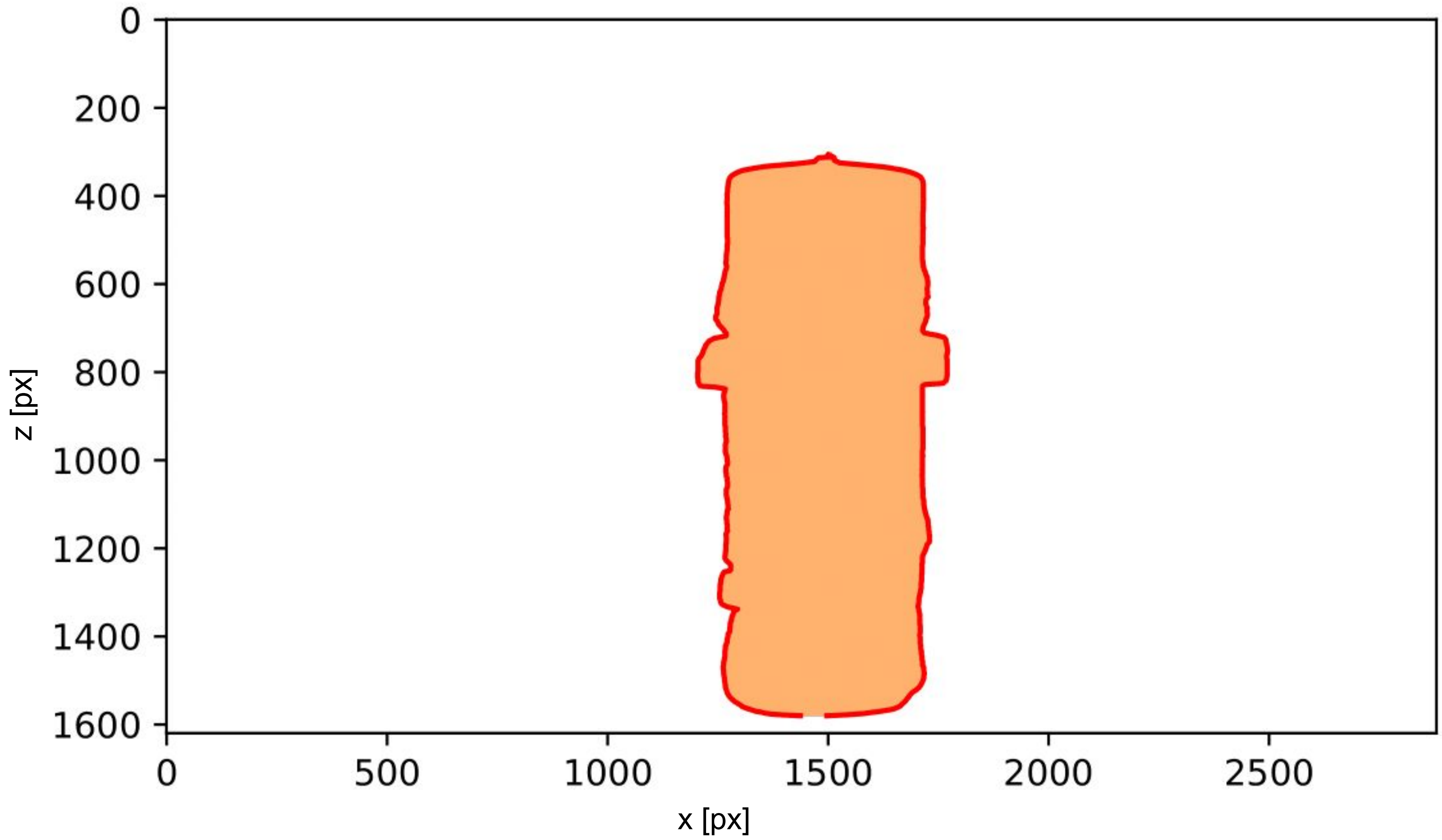

Diameter Data Test 1 (2024-07-26)
z-level 700
z-level 1100
z-level 1400
Burst time
570
560
550
540
530
520
510
500
Diameter [px]
13:59:58
14:03:06
14:06:17
14:09:23
14:12:31
14:15:40
14:18:52
14:21:59
14:25:12
Time [hh:mm:ss]



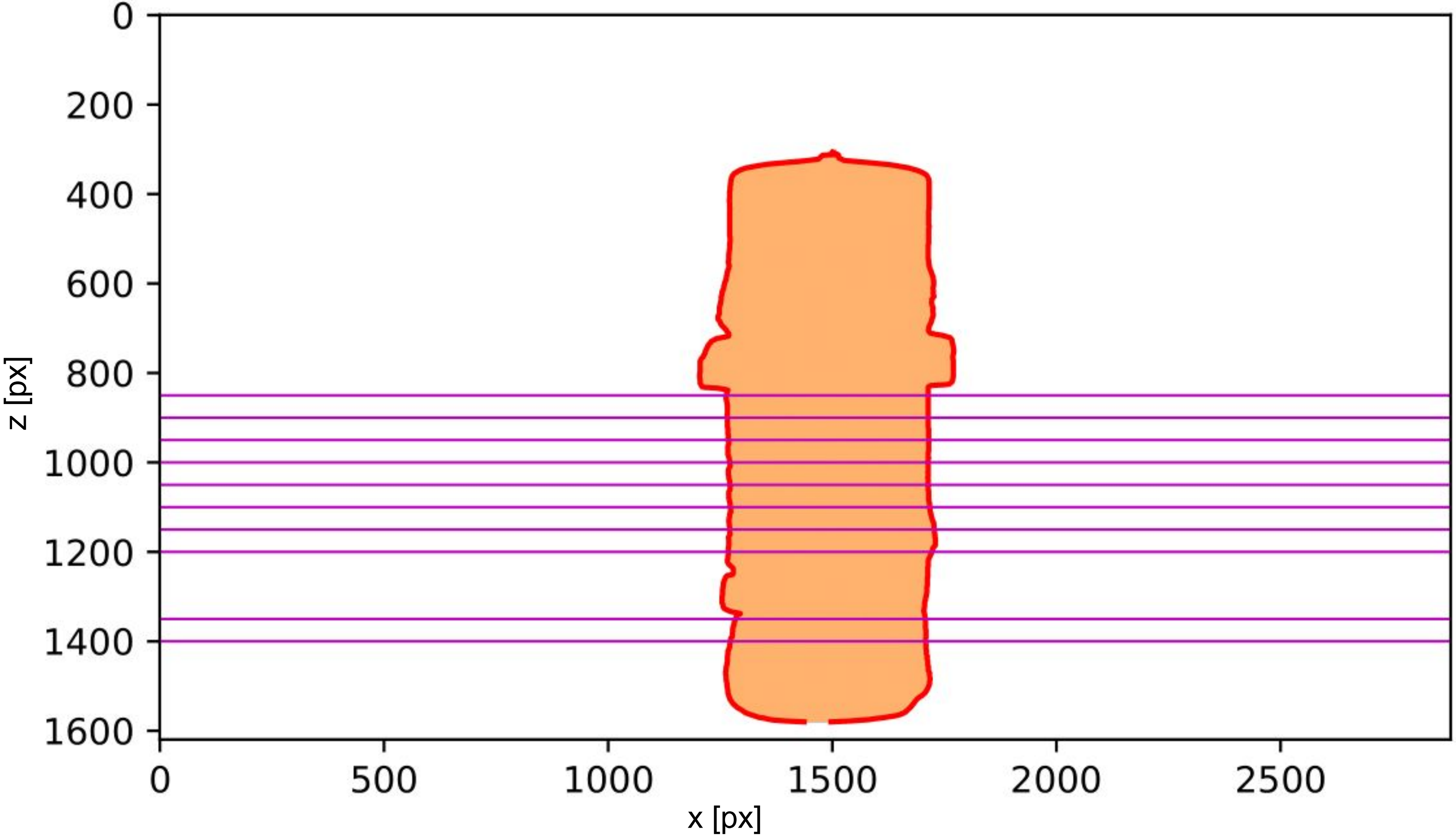
z [px]
x [px]
0
200
400
600
800
1000
1200
1400
1600
0
500
1000
1500
2000
2500
2024-08-29 14:00:52

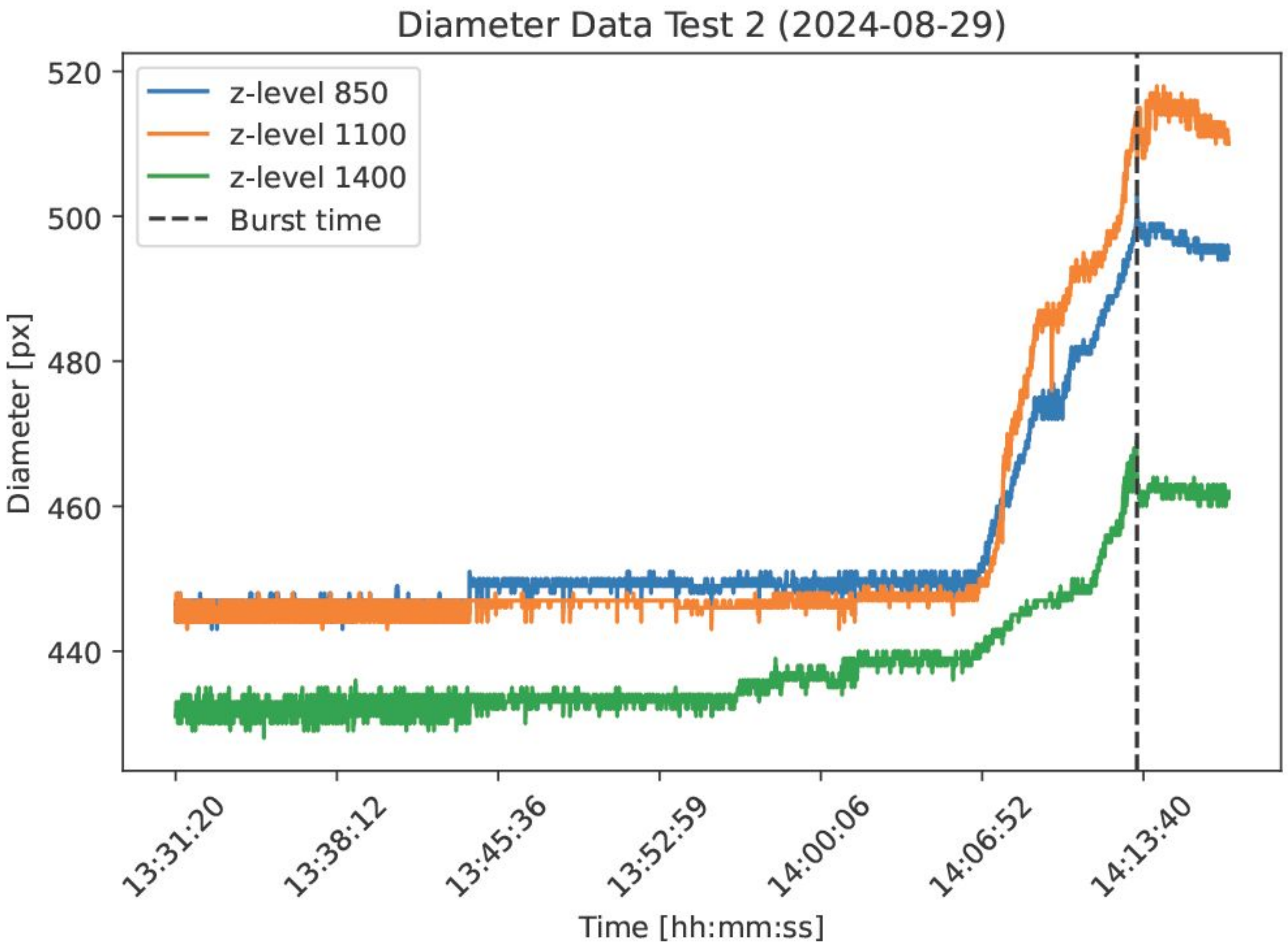


z [px]
x [px]
0
200
400
600
800
1000
1200
1400
1600
0
500
1000
1500
2000
2500
2024-08-29 14:00:52
PNL LC
CKT. 35



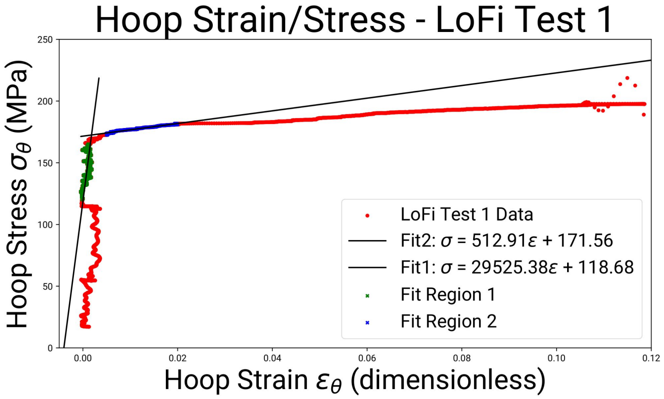
0
200
400
600
800
1000
1200
1400
1600
z [px]
0
500
1000
1500
2000
2500
x [px]

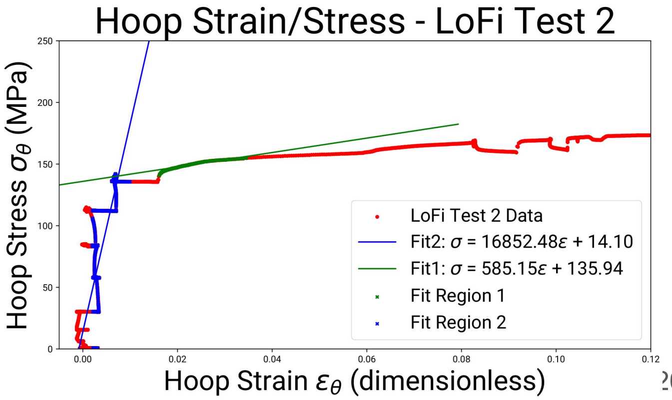

0
200
400
600
800
1000
1200
1400
1600
z [px]
0
500
1000
1500
2000
2500
x [px]


Diameter Data Test 2 (2024-08-29)
z-level 850
z-level 1100
z-level 1400
Burst time
Diameter [px]
520
500
480
460
440
13:31:20
13:38:12
13:45:36
13:52:59
14:00:06
14:06:52
14:13:40
Time [hh:mm:ss]

Under Pressure: Results of Physics-Based Analysis

- hoop stress vs hoop strain curve
  - hoop strain: $\epsilon_\theta(\tau) = \dfrac{D - D_0}{D_0}$
    - *D_0*: initial unpressurized diameter (152.4 mm)
    - *$D(\tau)$*: diameter as a function of time (and increasing pressure)
  - hoop stress: $\sigma_\theta(\tau) = \dfrac{PD}{2t}$
    - *P*: standard pressure
    - *t*: cylinder wall thickness (1.5 mm)
- stress–strain curves characteristic of OFHC copper used for cylinders
- yield strength found to be consistent with expectations of copper for the given geometry





Summary

- L1000 is an upcoming next-generation 0v□□ decay experiment
- to reach ultra-low backgrounds, high-purity materials must surround cryostat; to offset LAr costs, reentrant tube introduced into experiment design
- small-scale burst testing provided pressure data for LoFi cylinders but unreliable strain data
- SAM2 applied to video footage for two tests, and diameters extracted along with timestamps; physics-based strain anal
results met material expectations

- **computer vision models can be utilized for material parameter extraction**
- **video-based strain analysis viable as complementary diagnostic tool**