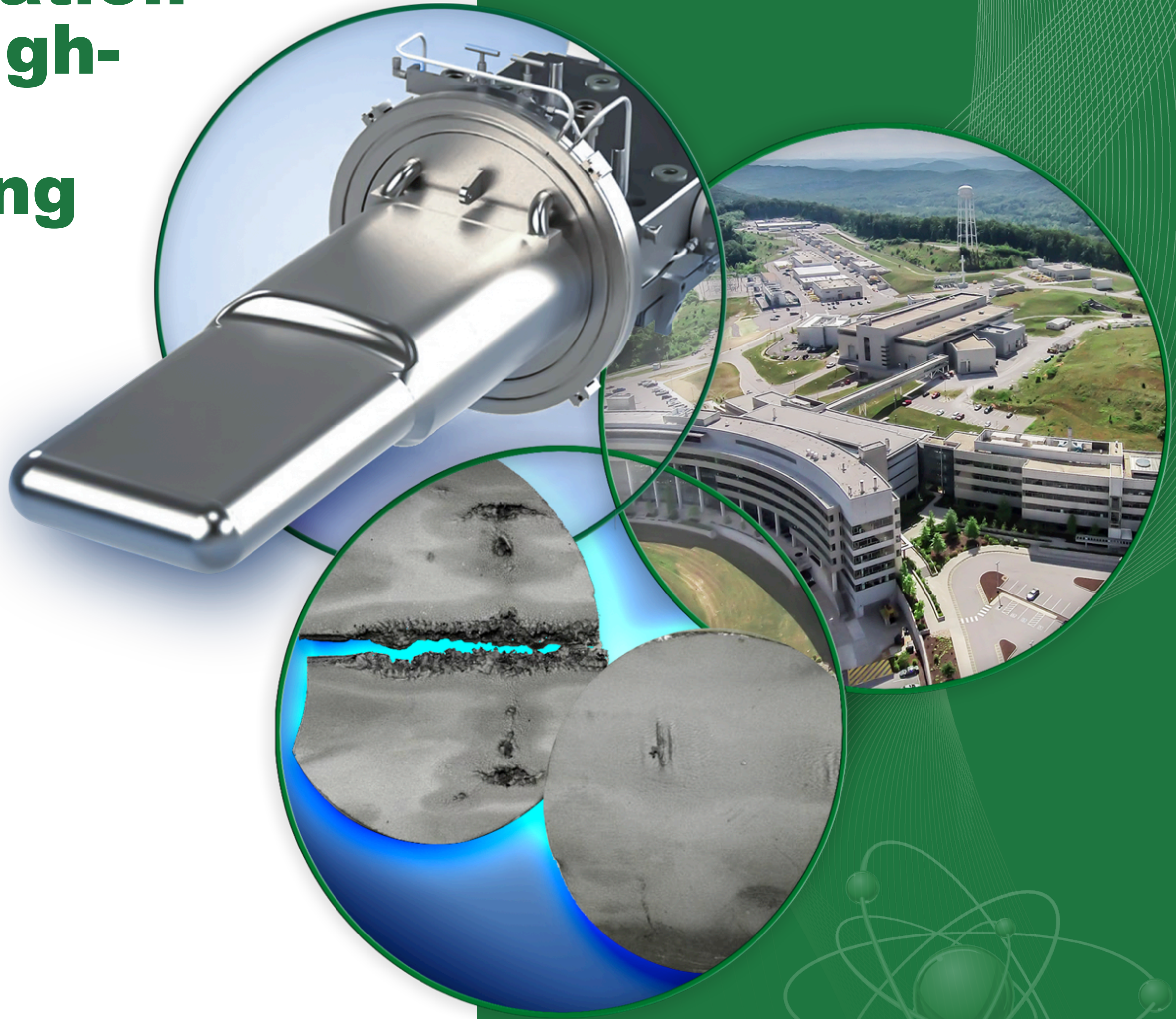
Tensile properties characterization of irradiated AISI 316L from high-use target modules at the Spallation Neutron Source using digital image correlation



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13th International Workshop on Spallation Materials Technology

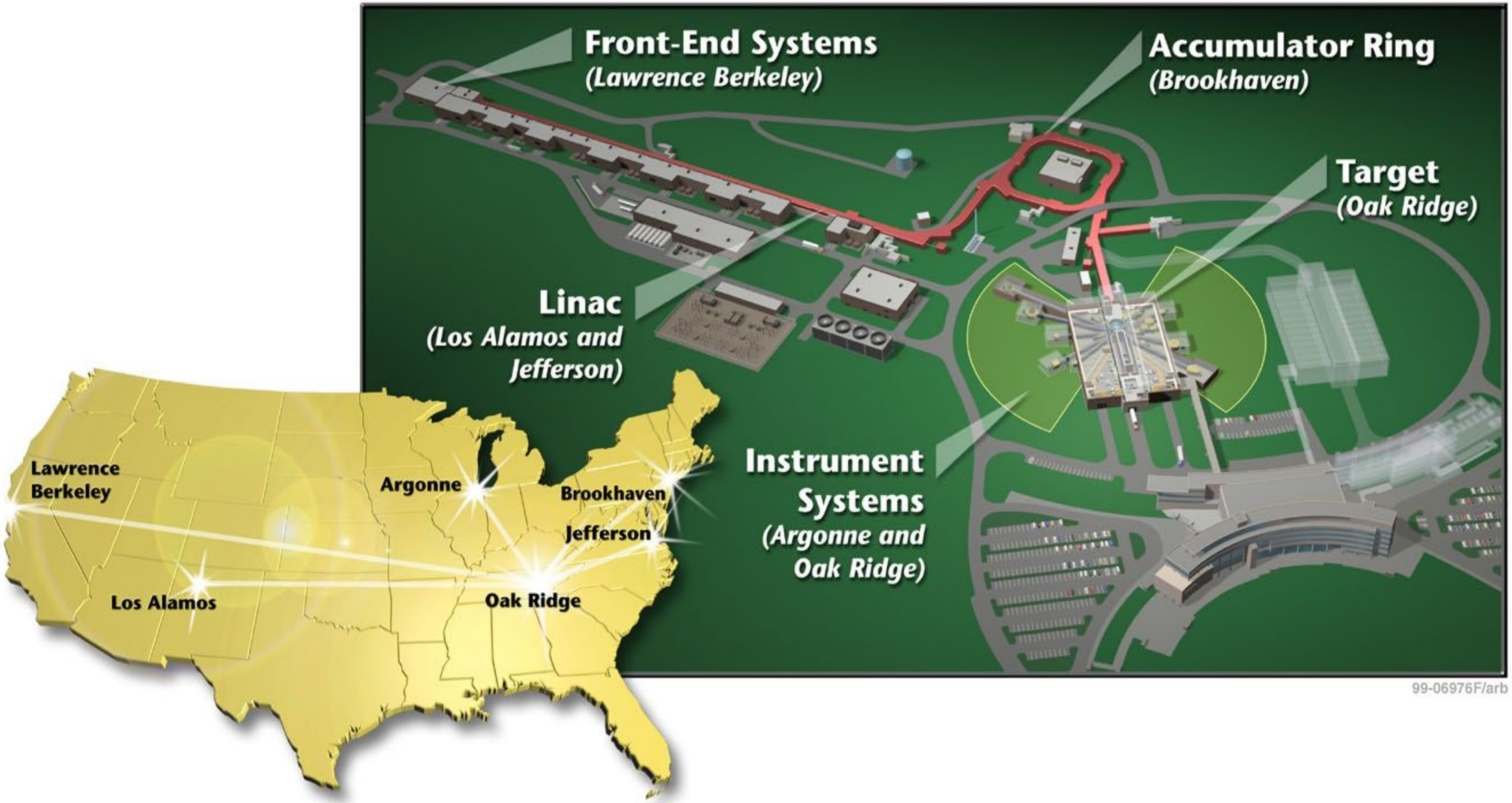
Chattanooga, Tennessee, USA

Outline

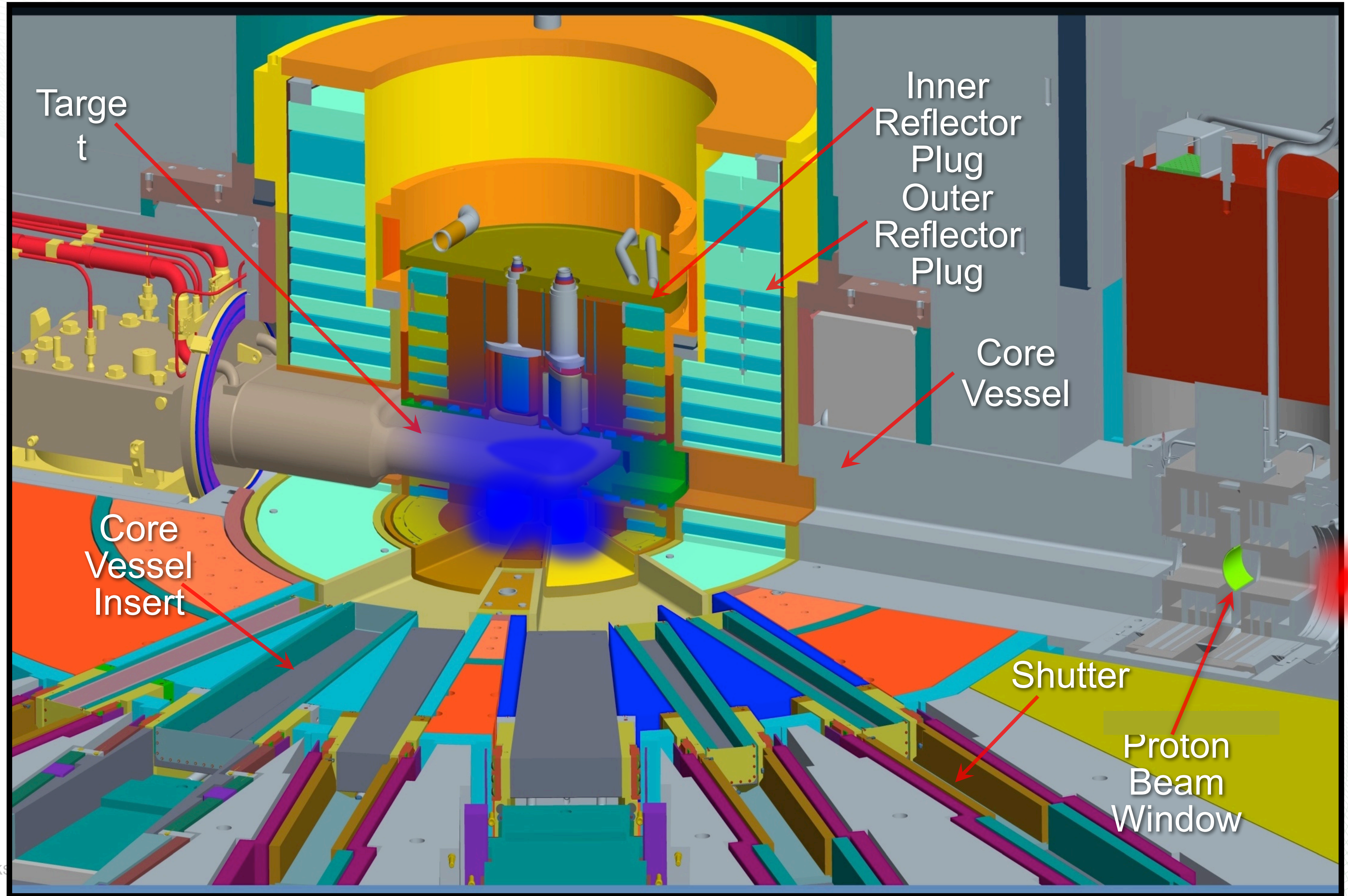
- Background on SNS Target and Previous Work
- Target Sampling and Testing Procedures
- Results
  - Tensile Testing
  - Digital Image Correlation Analysis
- Summary

The Spallation Neutron Source is a megawatt class accelerator-based pulsed neutron source

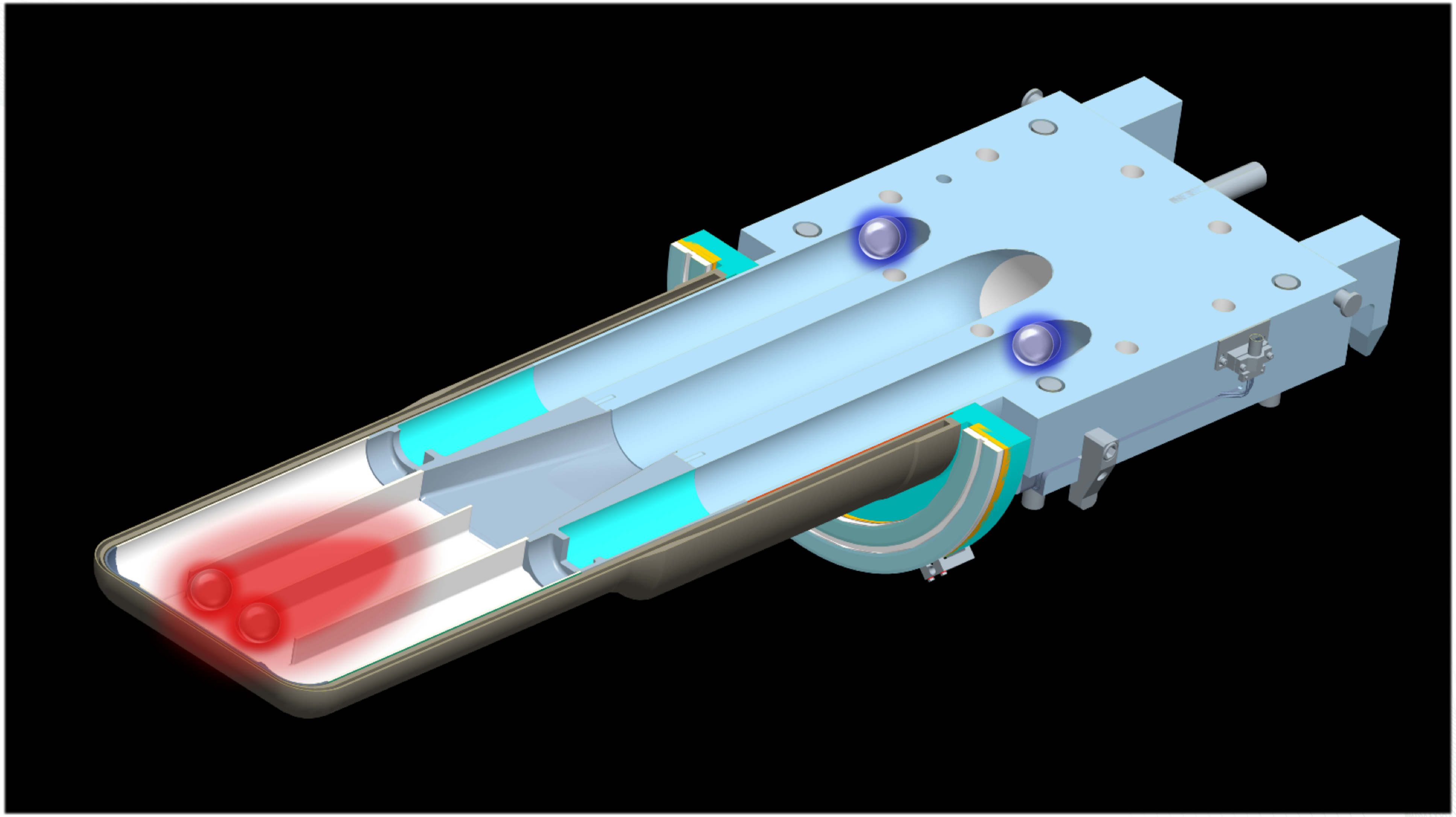
- Neutrons are produced via high-energy spallation reactions induced by injecting 1 GeV protons into liquid mercury at a frequency of 60 Hz



The target provides neutrons to 24 beam lines



Mercury enters through side supply passages and returns through the center return passage



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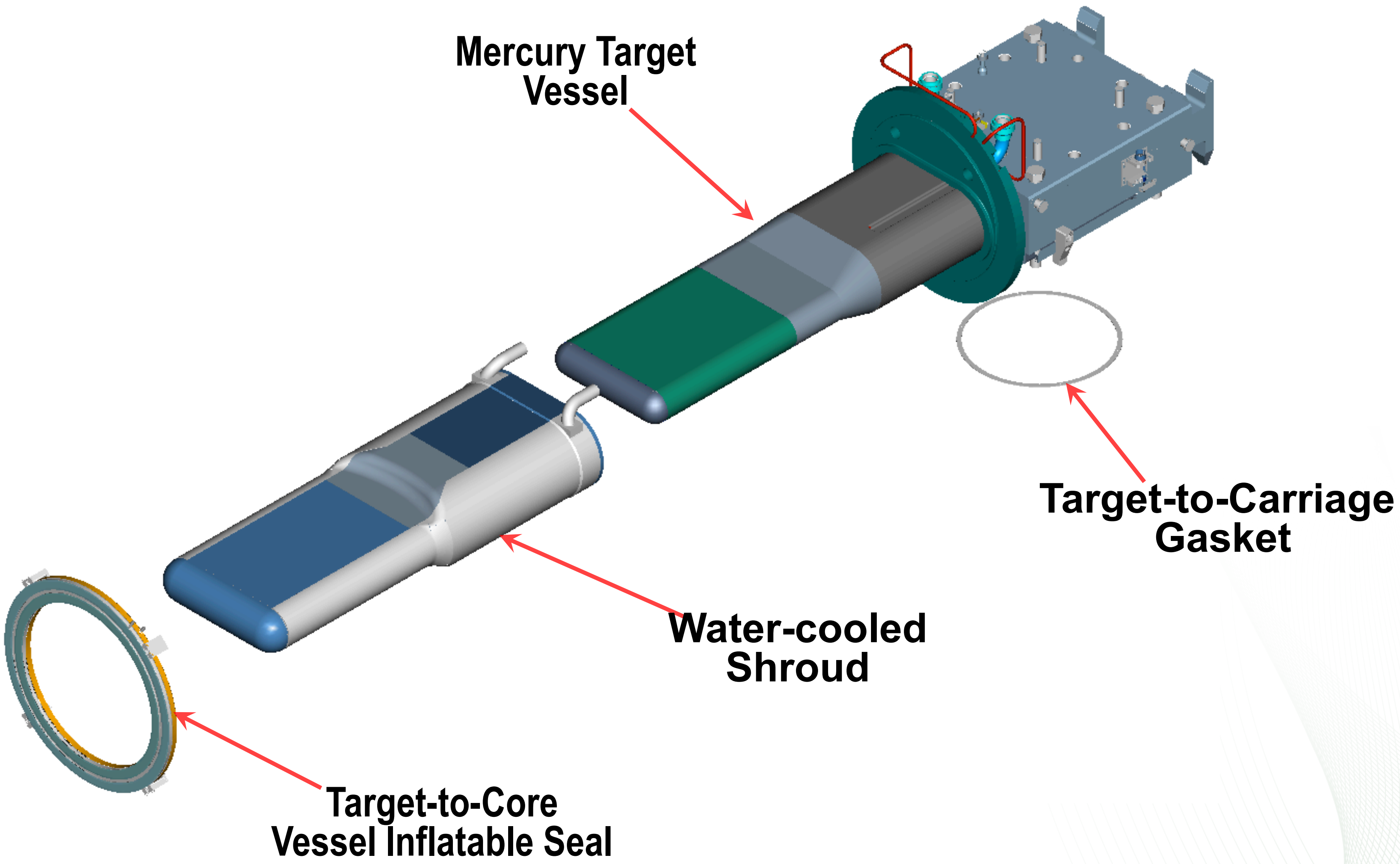
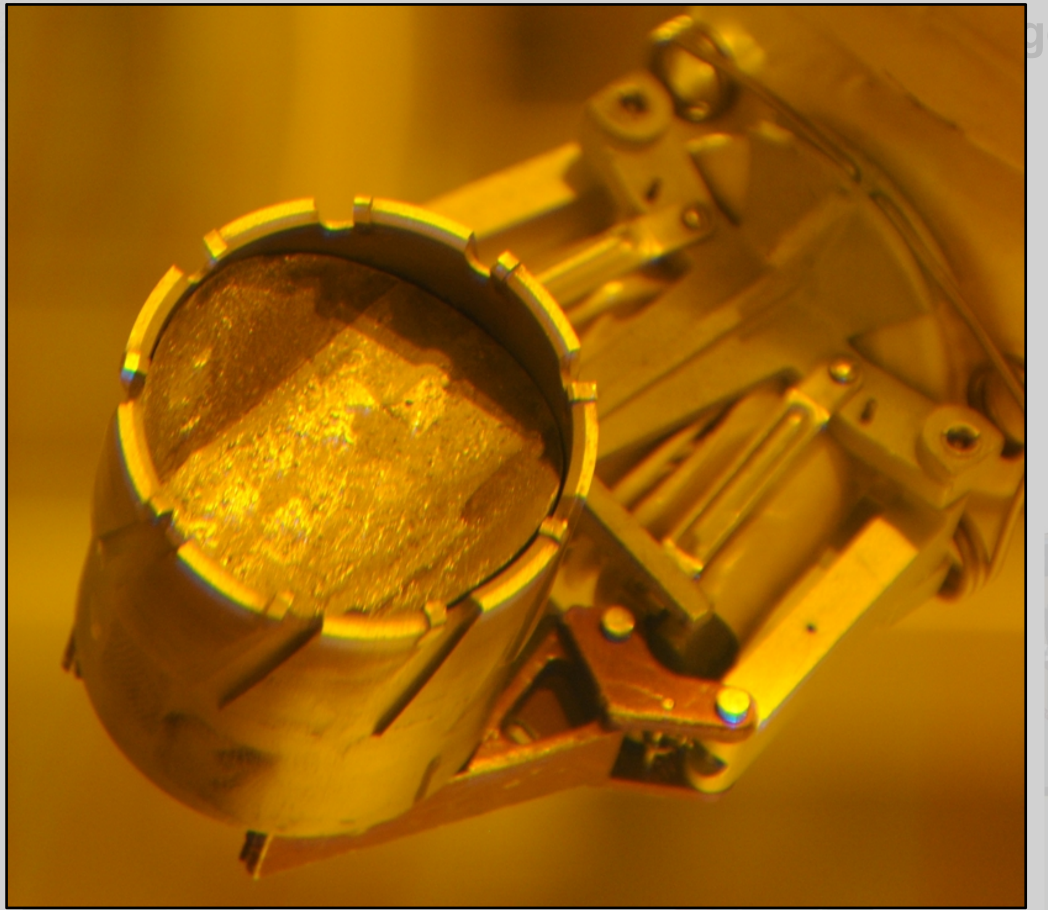
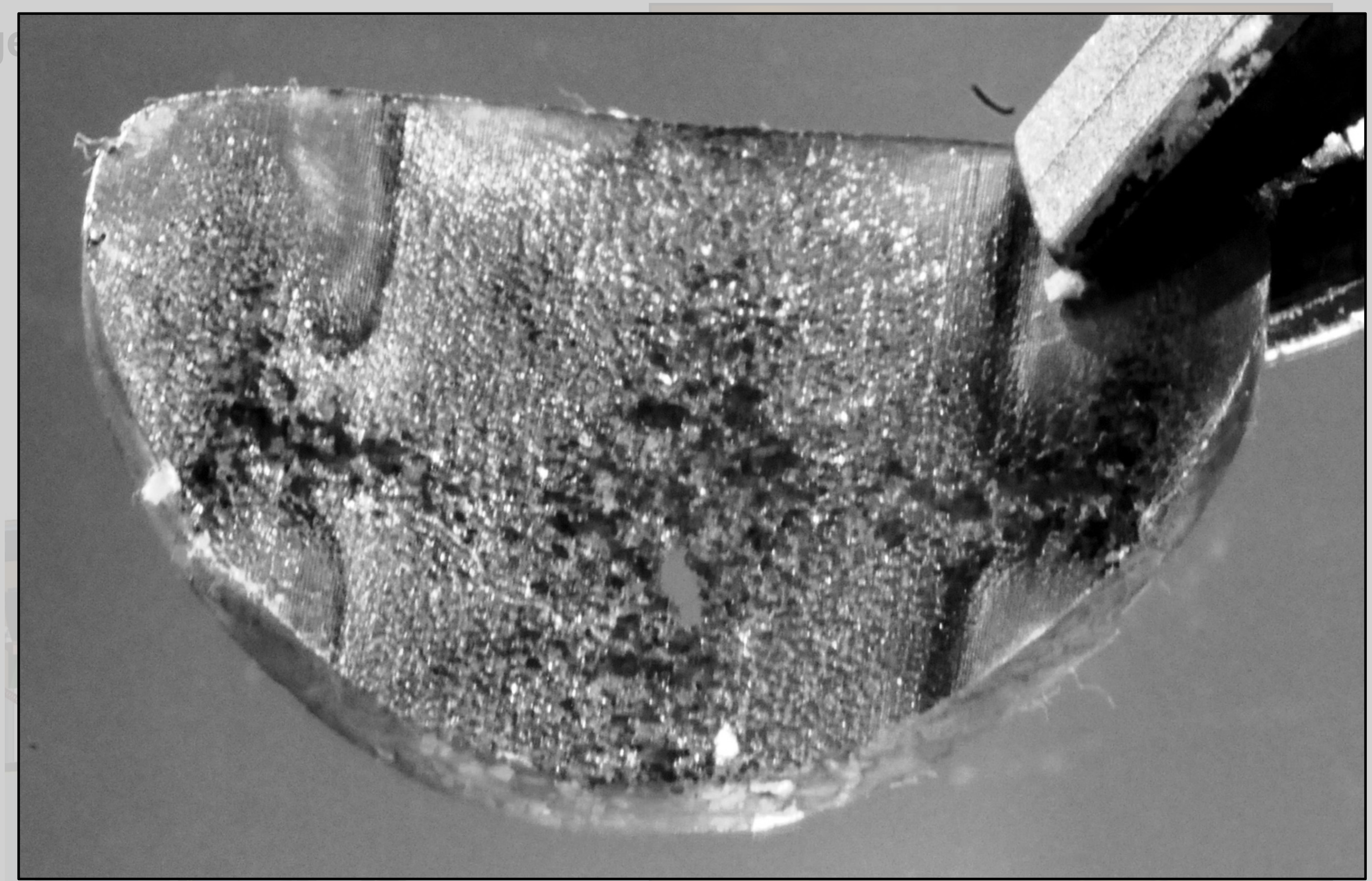
SNS target is composed of two "vessels" welded to a manifold block



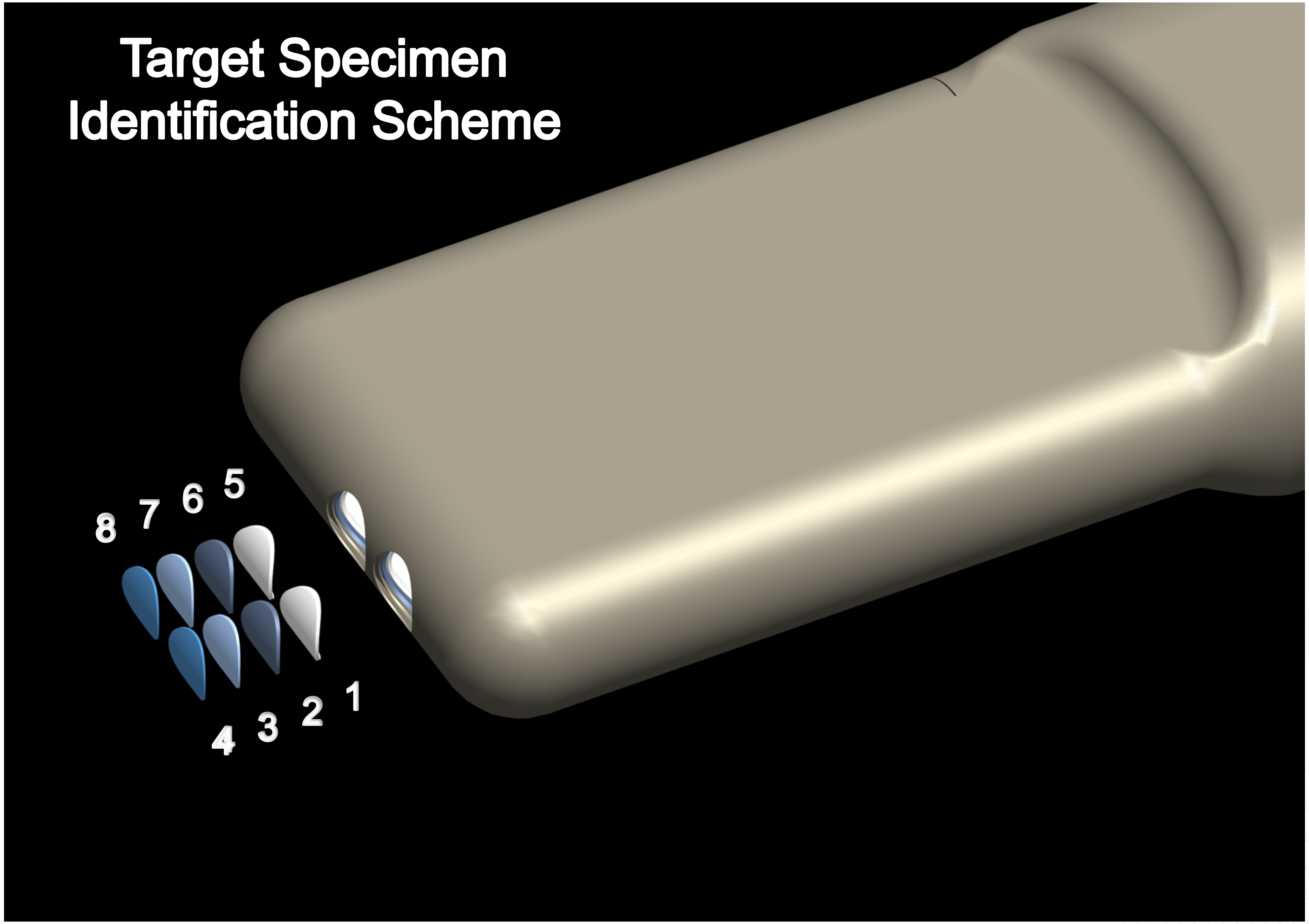
Disk-shaped Specimens are Routinely Sampled from the Beam Entrance Region of SNS Targets After Service





Pneumatic
Piston

Four disk-shaped specimens were removed from the target module by each cutter



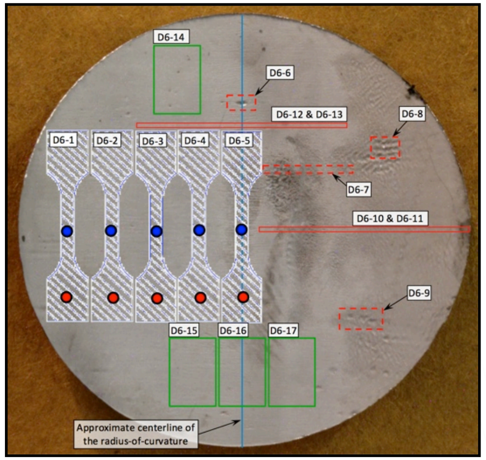
The SNS has secured several contracts with BWXT in the past to perform detailed PIE characterizations on target specimens

- The disks were cleaned in an ultrasonic bath and photographed; the images were used to produce specimen maps for each disk
- Specimen machining maps were produced for each disk and test specimens were machined via electrical-discharge machining (EDM)
- Several characterization techniques have been employed, including: tensile testing, hardness testing, SEM examination of cavitation pitting, surface replication/SEM examination, and inclusions characterization

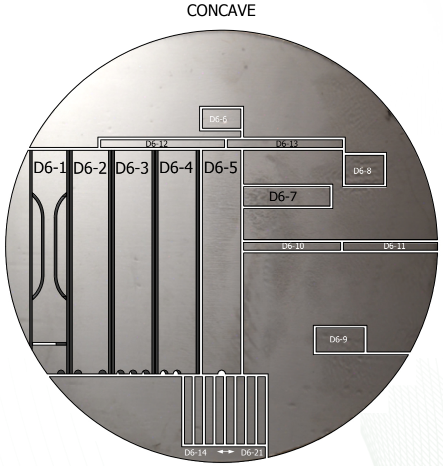
<u>Example: Disk 6 from Target 2</u>

Before Cleaning

After Cleaning

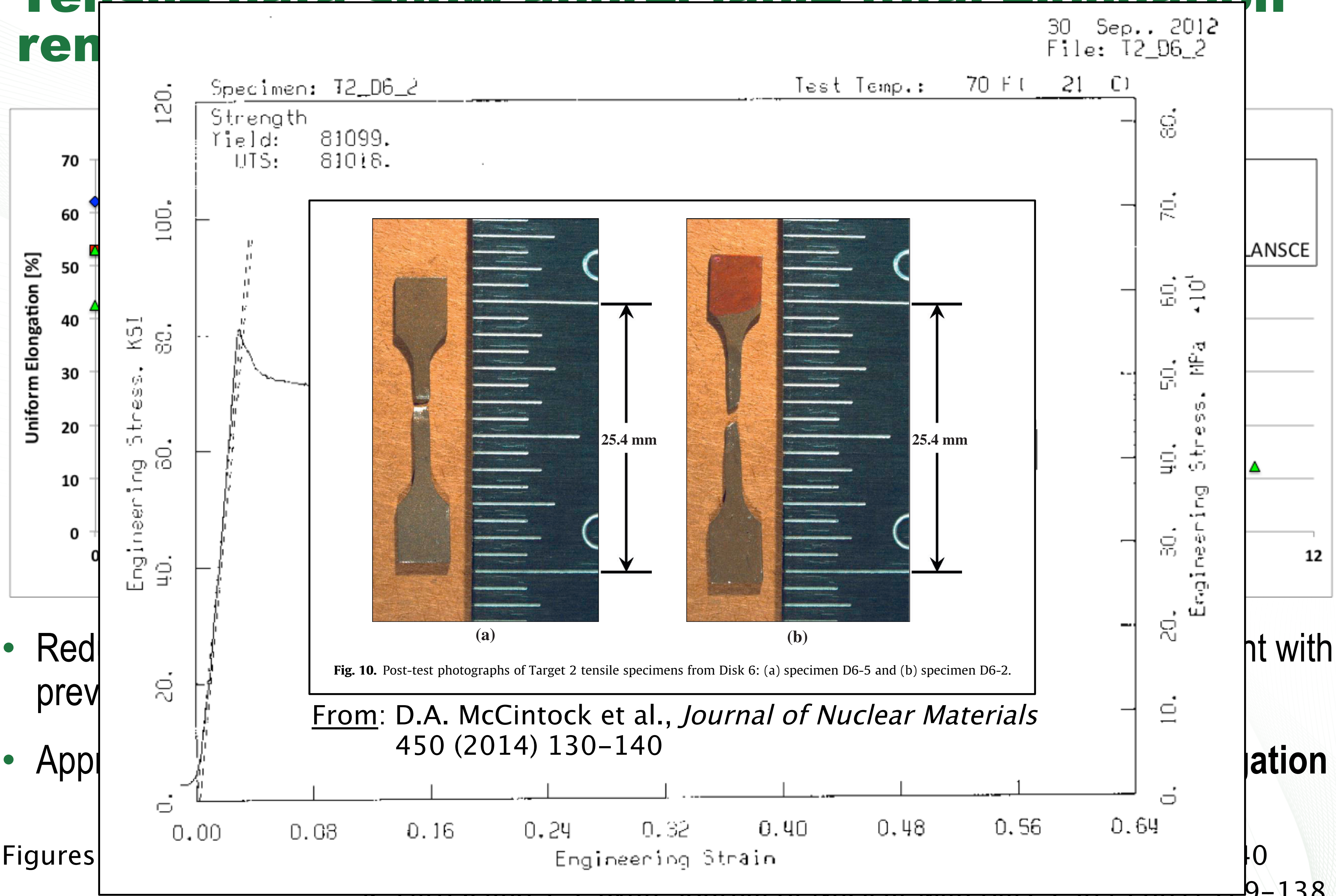


Specimen Map



EDM Machining Map

Tensile data show appreciable total elongation
ren…

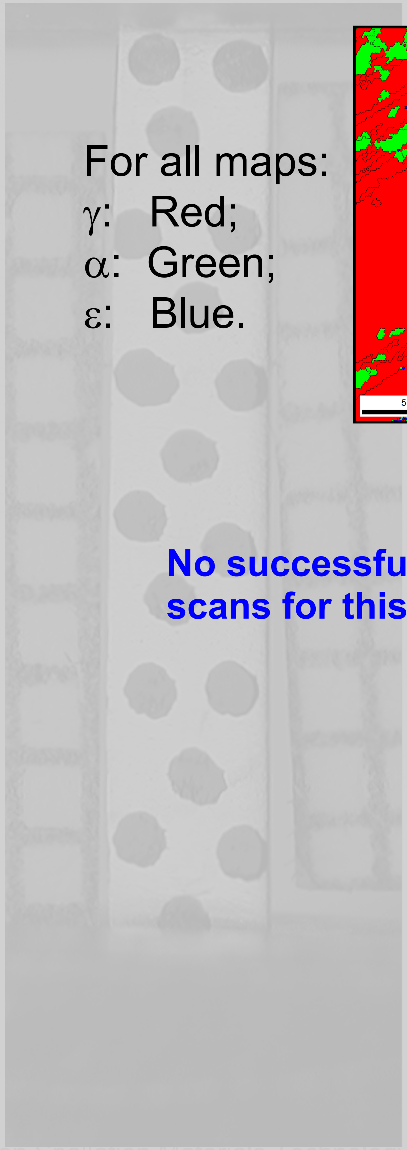


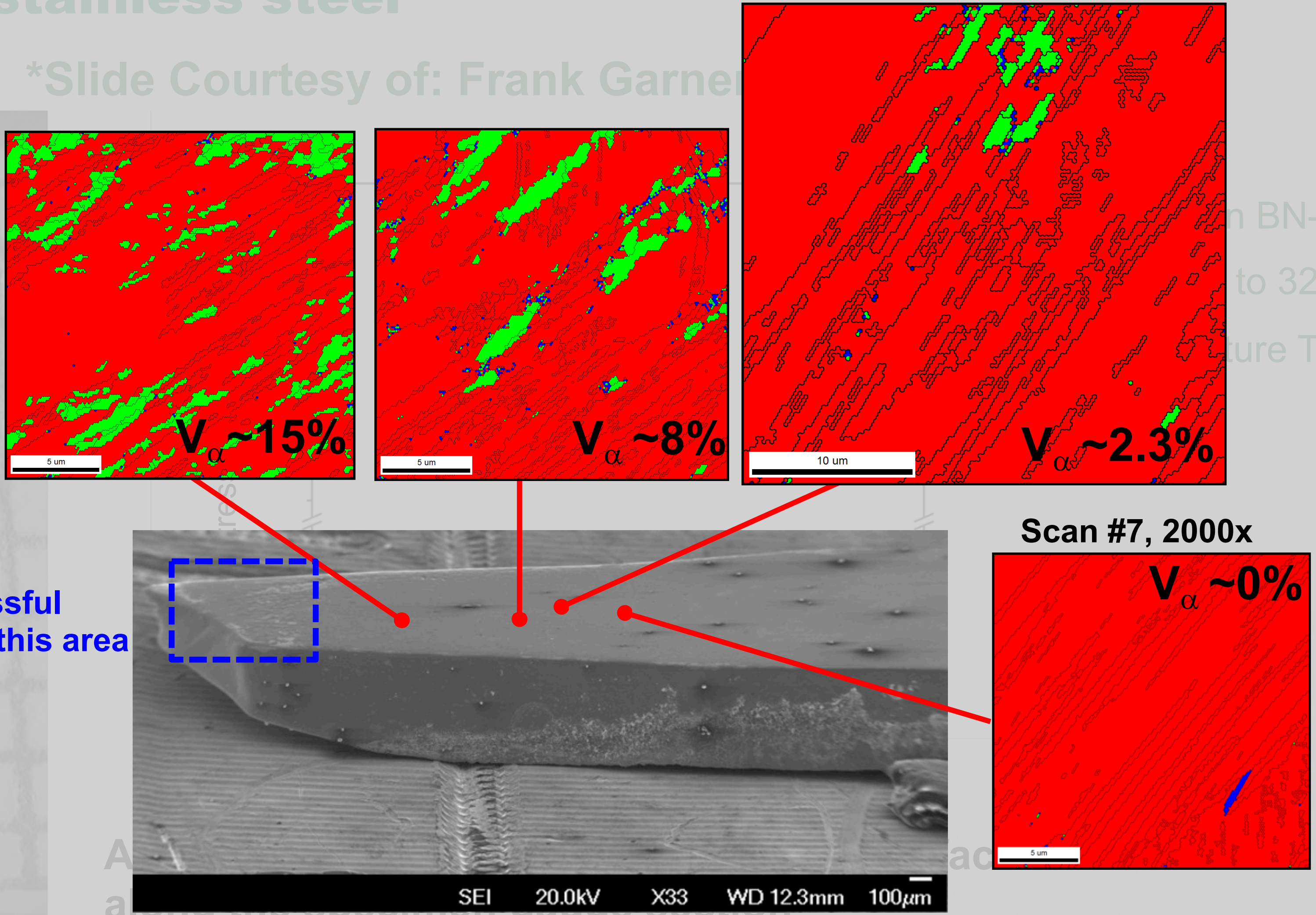
- Red… …nt with prev…
- Appr… …gation

Figures … …40
R. Farrell and T.S. Byun, *Journal of Nuclear Materials*, 296 (2001) 129–138

Inability to neck produces a "deformation wave" in highly irradiated stainless steel*

*Slide Courtesy of: Frank Garner





n BN-350

to 321 stainless steel

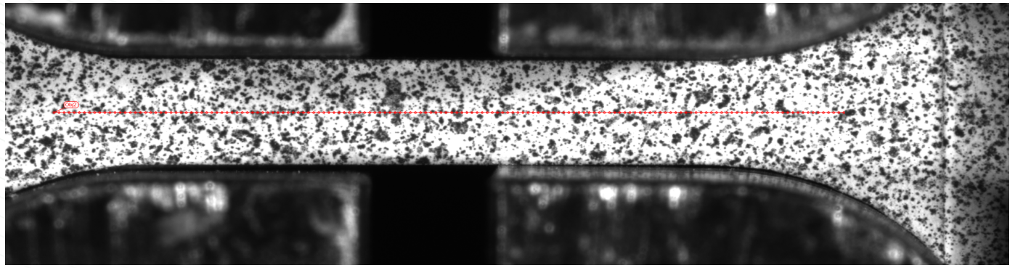
ure Test

A ... ac ... along the specimen gauge section

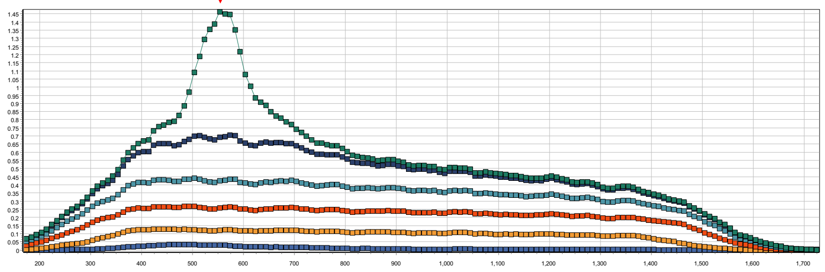
Gusev et al., J. Nucl. Mater. 386–388 (2009) 273–276
Gusev et al., J. Nucl. Mater. 403 (2010) 121–125

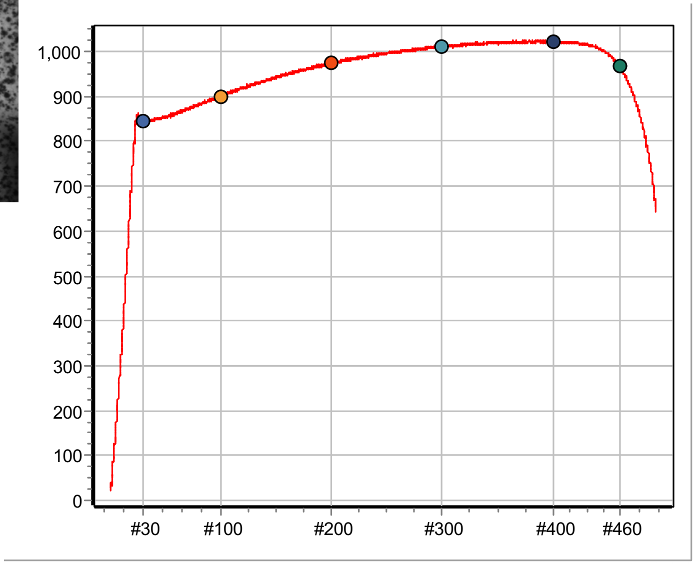
Digital image correlation (DIC) is an extremely powerful tool for analyzing deformation behavior

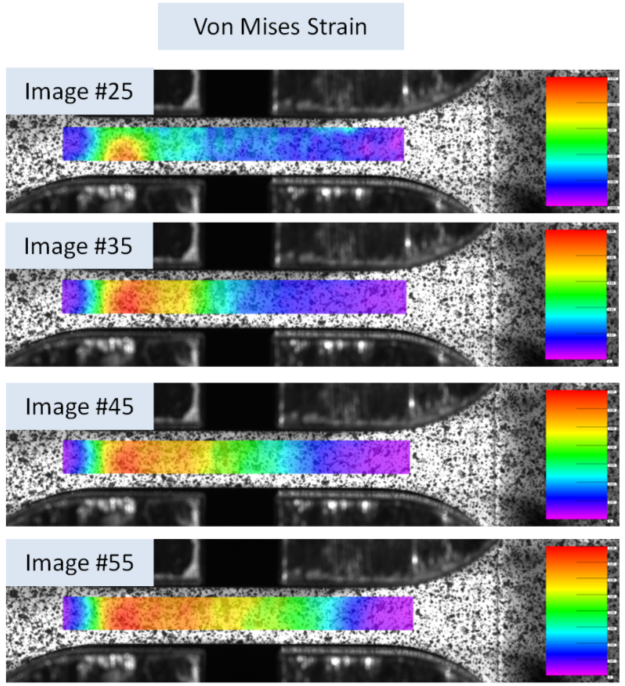
- DIC allows for analyzing deformation localization in detail, calculating strain distribution along the specimen gauge, strain rate maps, etc.



Neck Formation







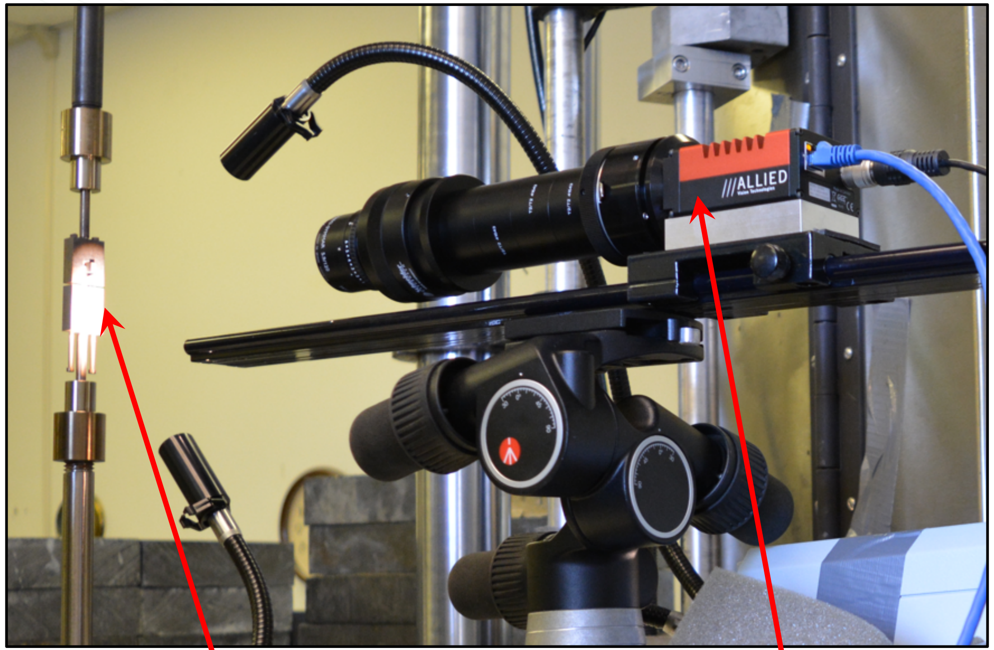
- Strain distribution (von Mises strain, Green-Lagrange strain tensor)
- Subset 63 pix. Raw data! No smoothing/manipulations.

- **32 irradiated specimens were tested using DIC – at the moment, the largest dataset for the irradiated austenitic steels**

Tensile specimens were prepared for DIC characterization

- Digital Image Correlation (DIC) was used to characterize specimen deformation behavior during testing
  - High-resolution camera captured one image per second during test
  - Image data reveals strain behavior of the entire specimen during test
- Tensile specimens were painted to provide contrasting features for analysis software to track and calculate displacements

DIC Testing Setup

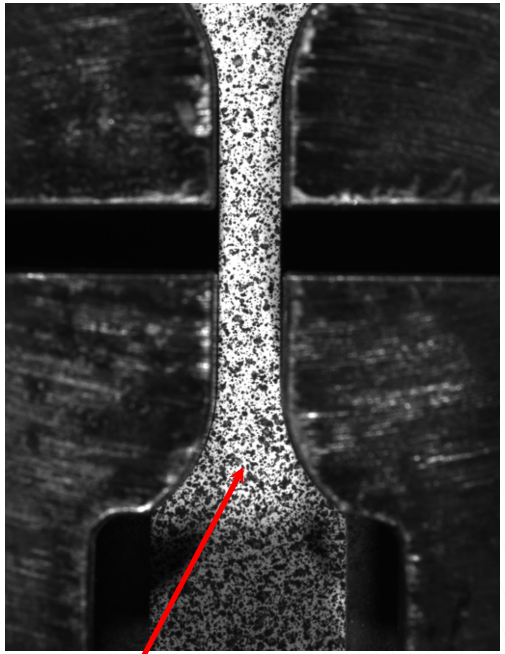


Tensile Specimen

High-resolution Camera

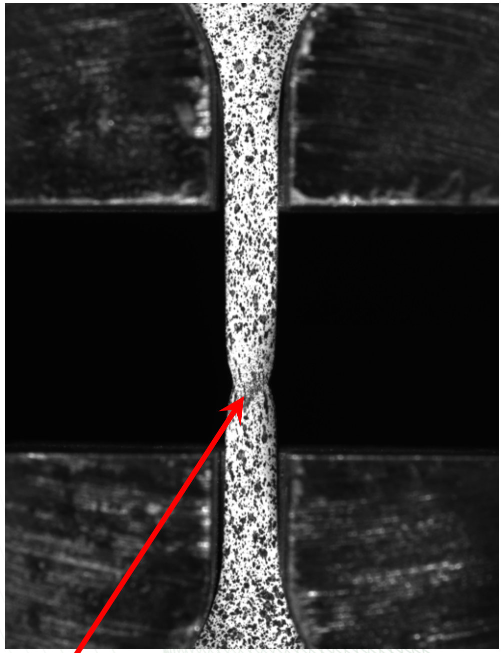
Target 8 Specimen

Beginning of Test



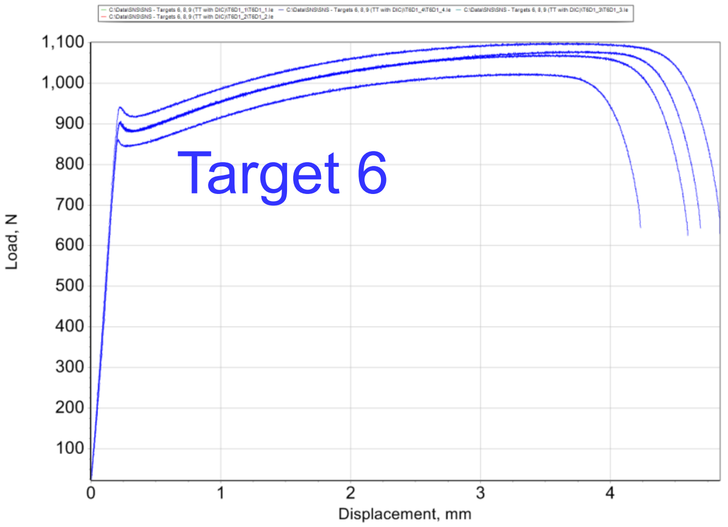
Tensile Specimen in Testing Fixture

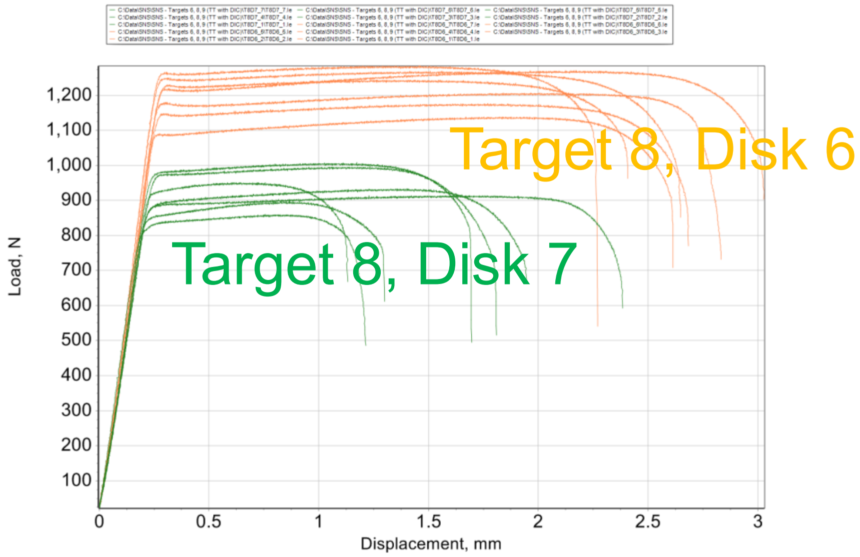
End of Test



Neck at Specimen Failure Location

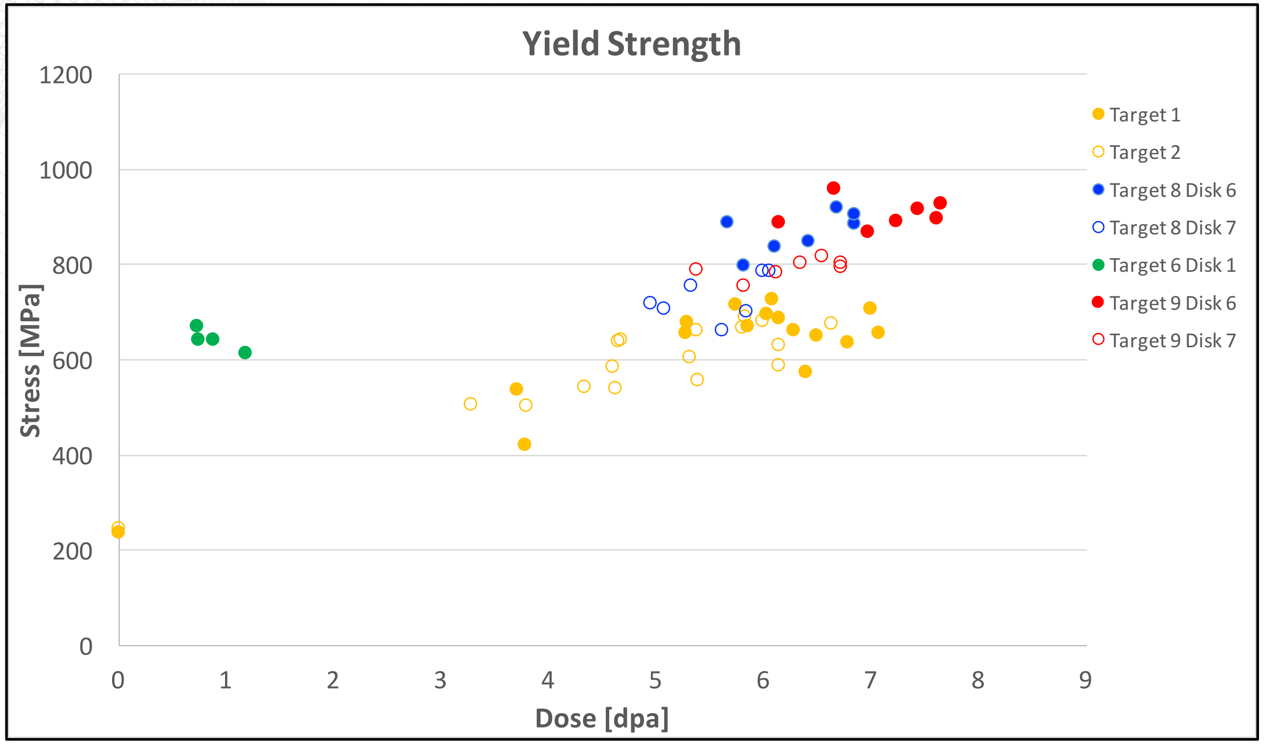
Engineering stress strain curves show similar general deformation behavior

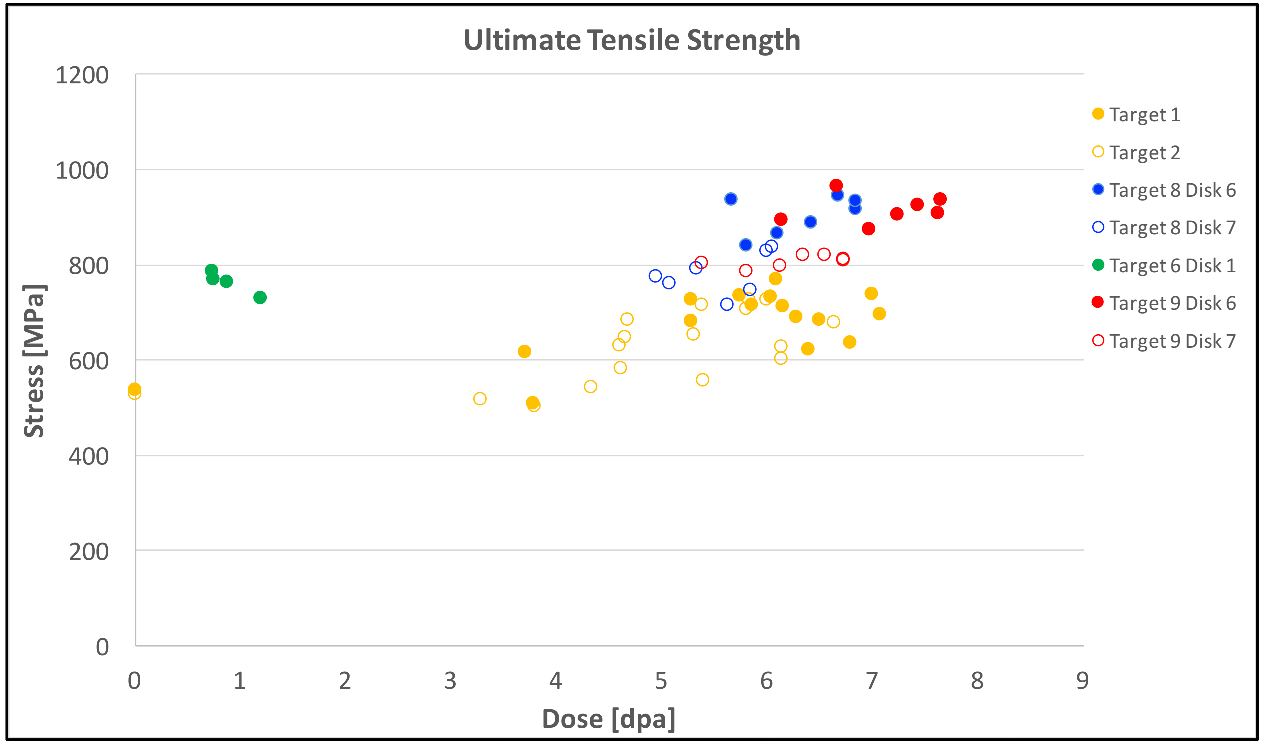




- Shapes of curves were quite similar, with a load drop shortly after yield
- Only Target 6 specimens (0.75 – 1.2 dpa) had appreciable strain-hardening after yielding

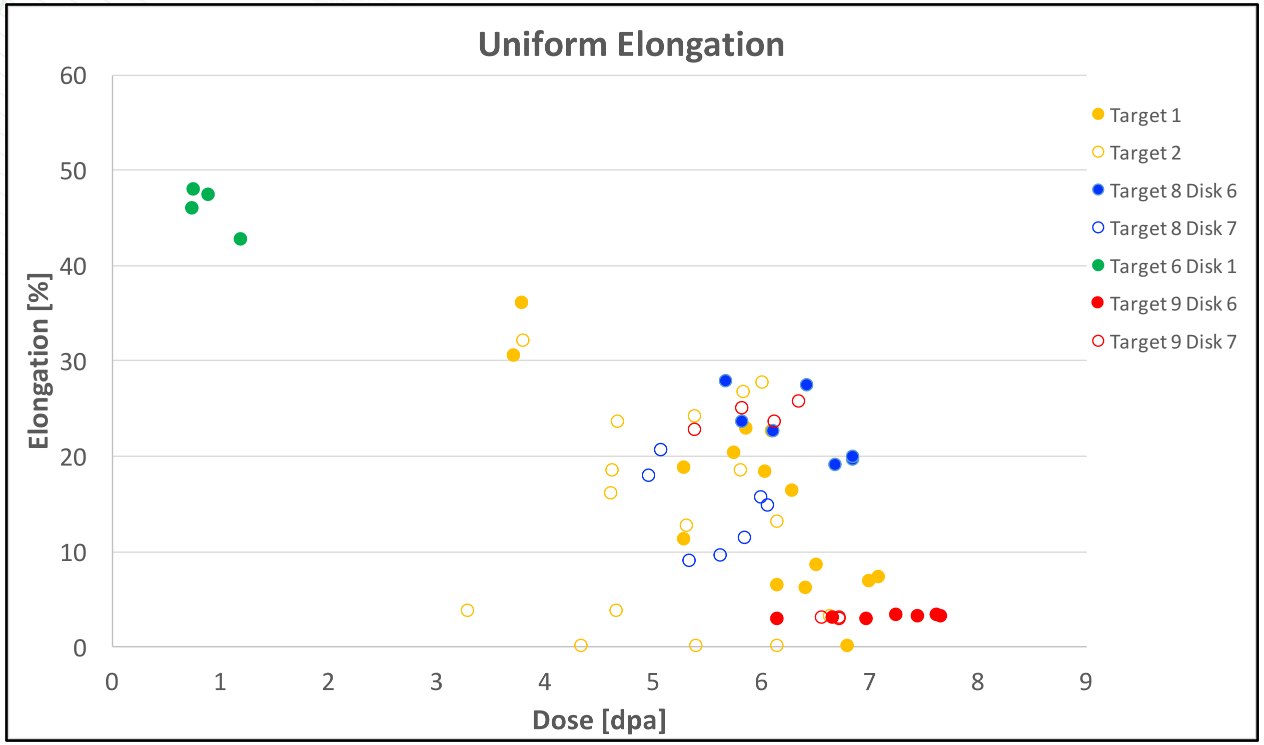
Increases in yield and ultimate strengths were observed

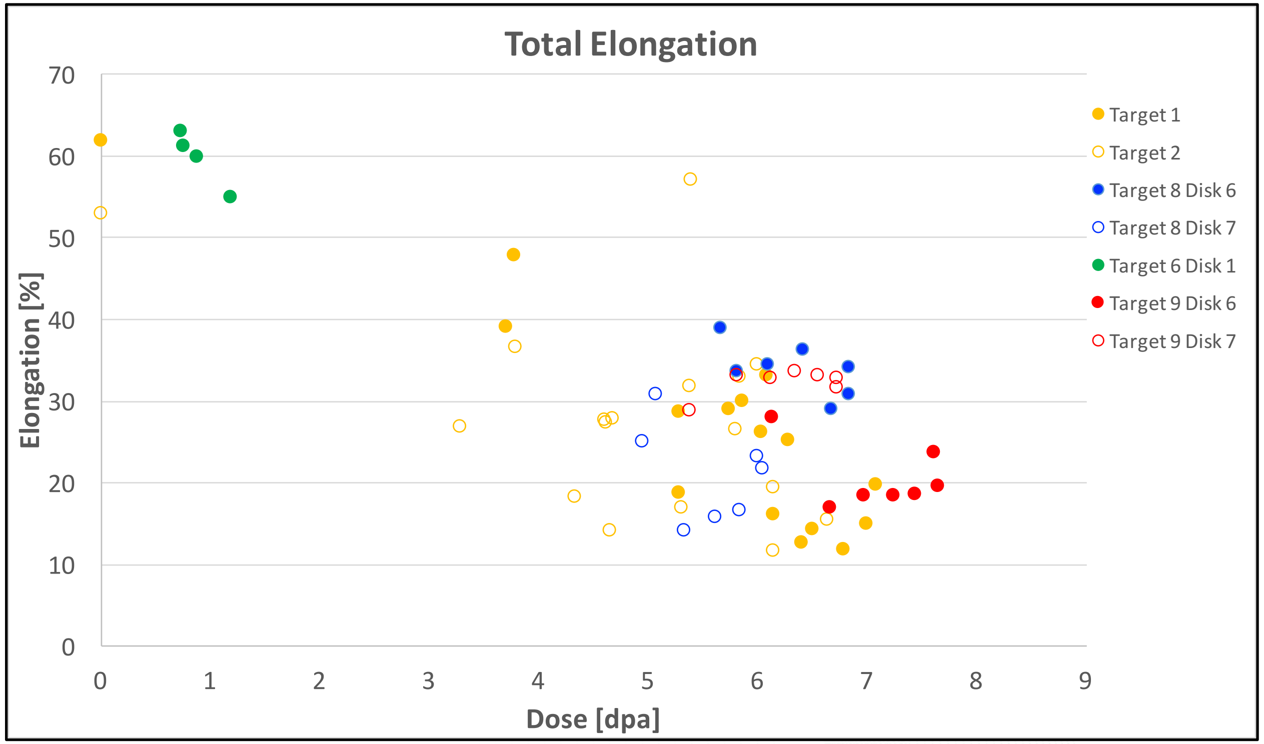




- Typical “low temperature” hardening was observed

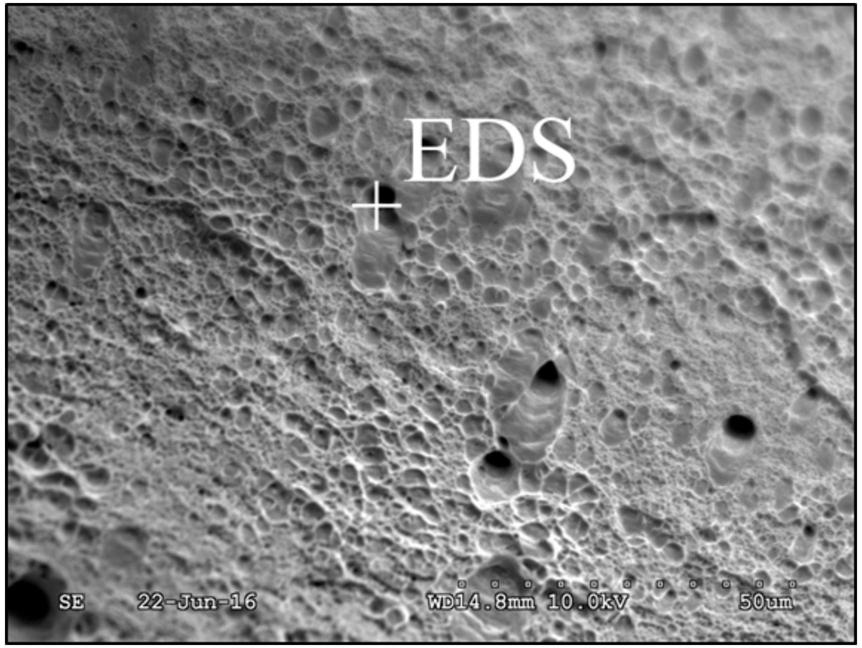
Elongation results show appreciable ductility remained in 316L target material up to ~7.6

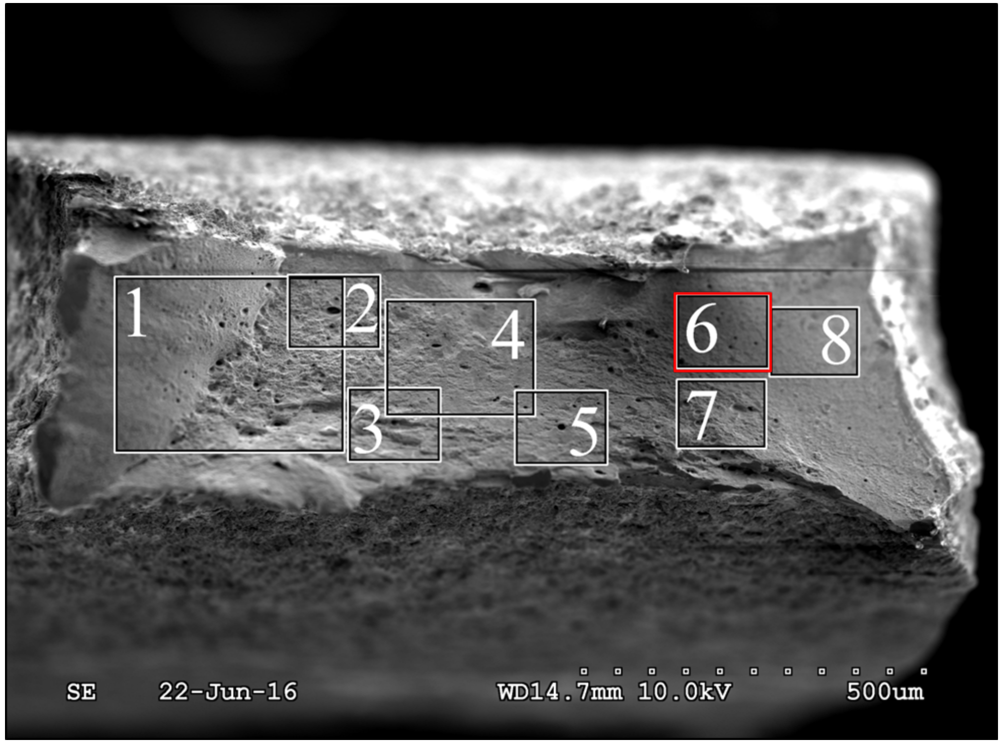


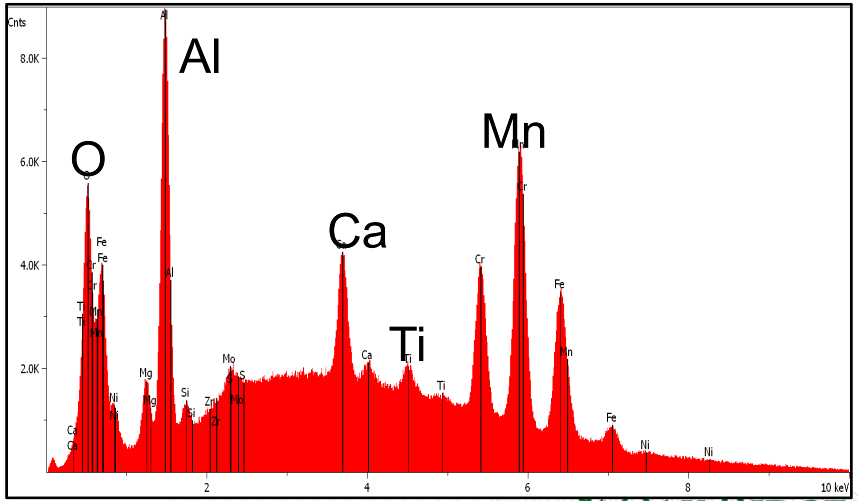


Fracture surfaces were examined via scanning electron microscopy

- All specimens fracture surfaces were primarily ductile microvoid coalescence morphology
- Inclusions rich in manganese, calcium, aluminum, silicon and titanium were identified via EDS

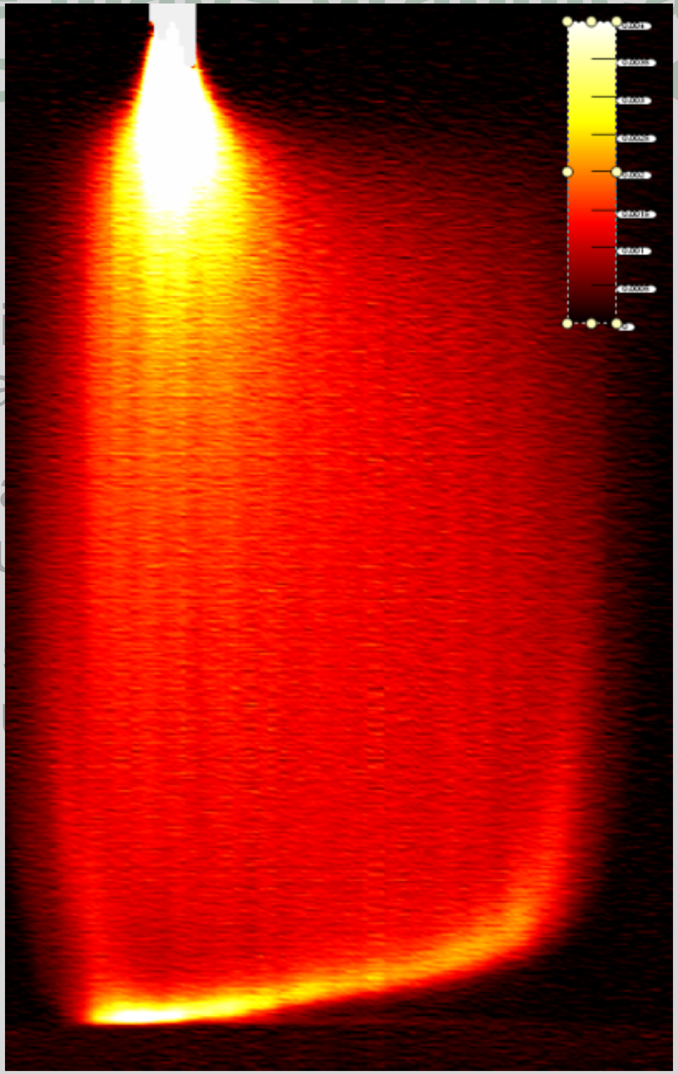


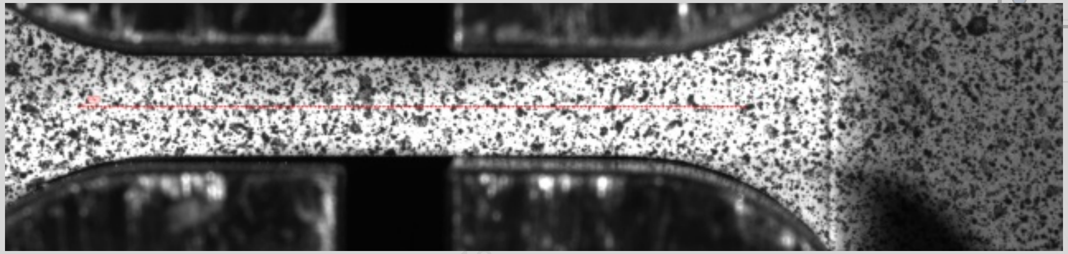


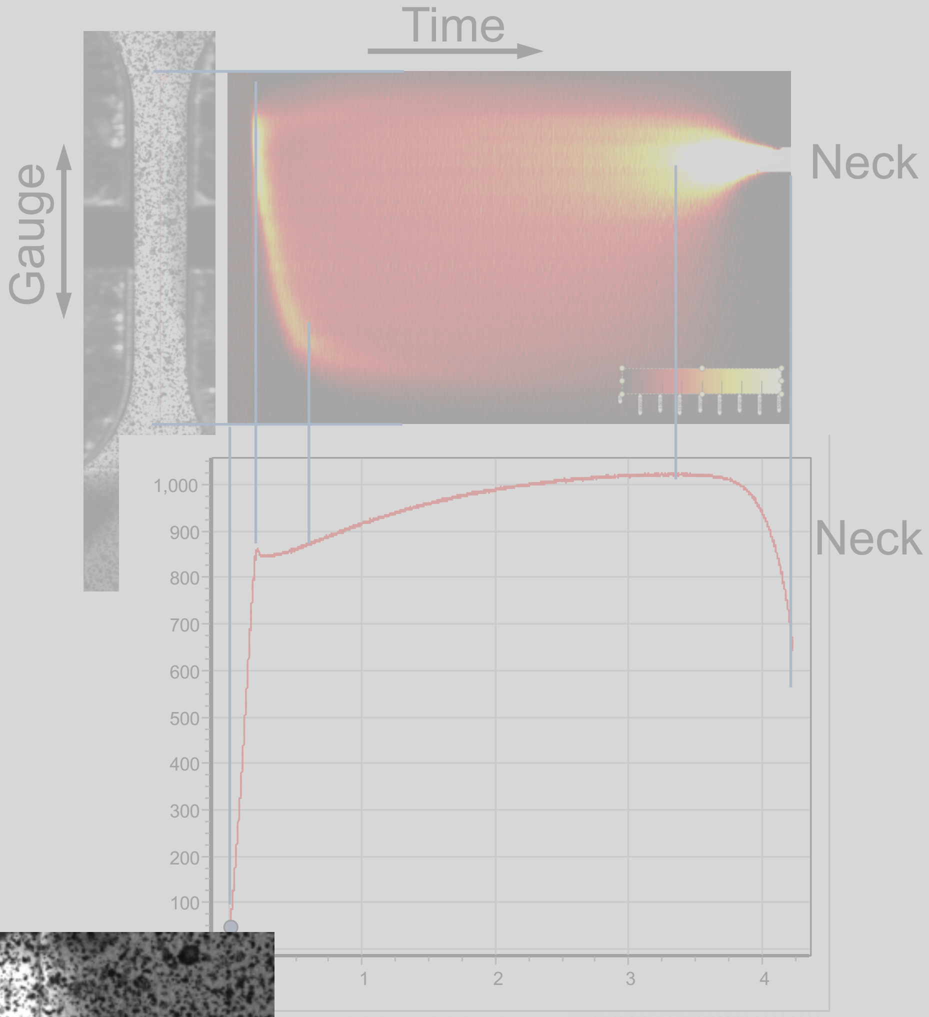


Strain rate maps graphically illustrate the deformatio ensile specimens

- Strain rate maps illustrate the gauge section during testing, propagation of deformation ba
- Elastic strain region is visible practically zero strain rate valu
- Neck evolution is also clear vi deformation in some area red







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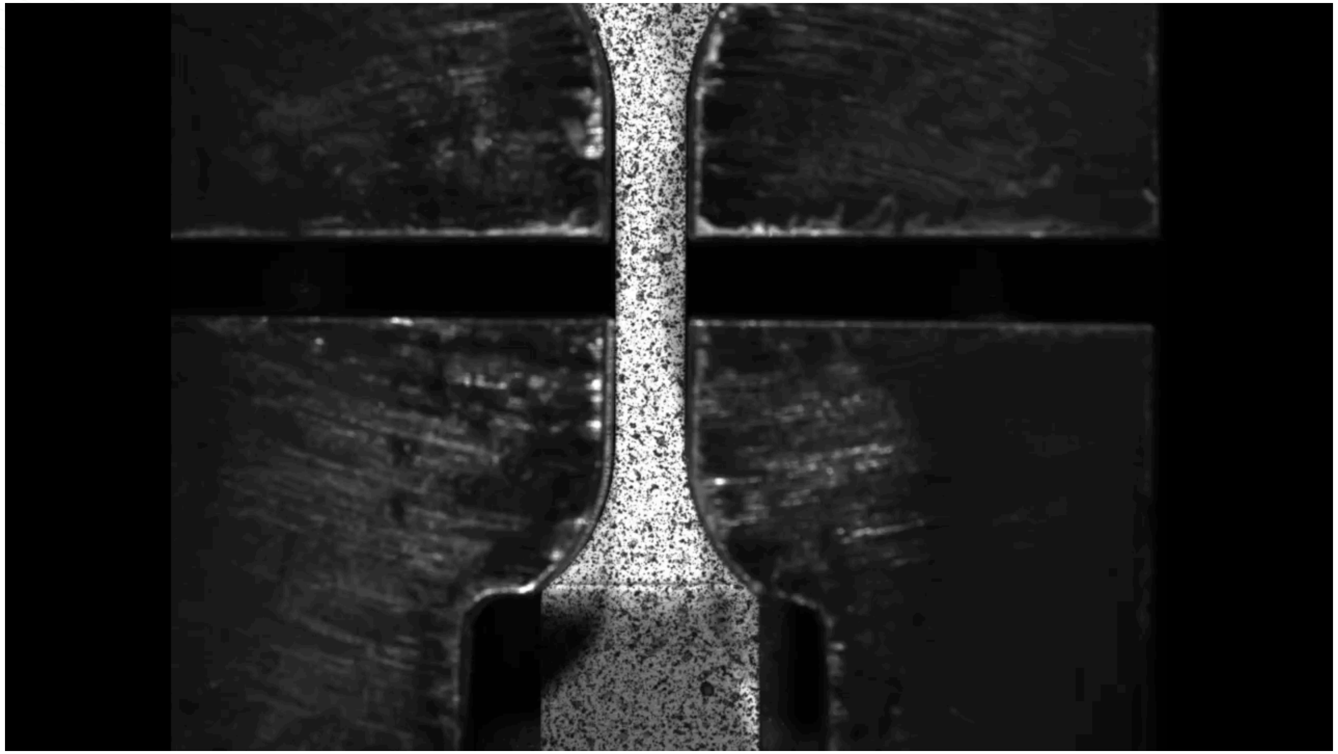
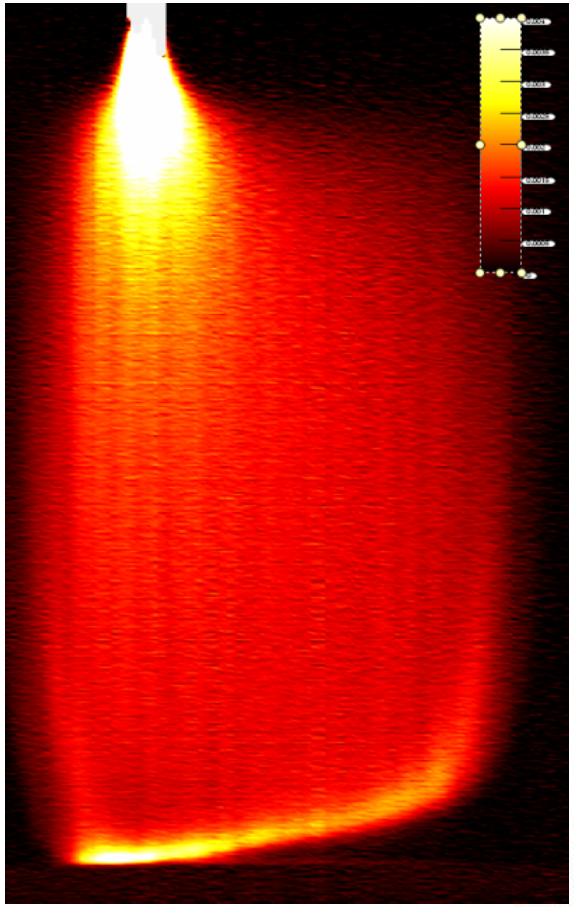
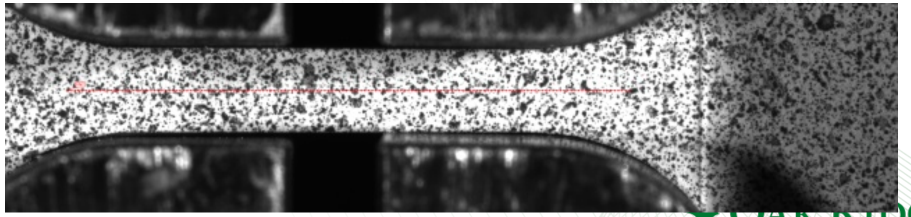
Specimens from Target 6 demonstrated moderate deformation band behavior

- At the beginning of test some Target 6 specimens displayed moderate deformation band behavior



Target 6, D9-1, TE = ~13%





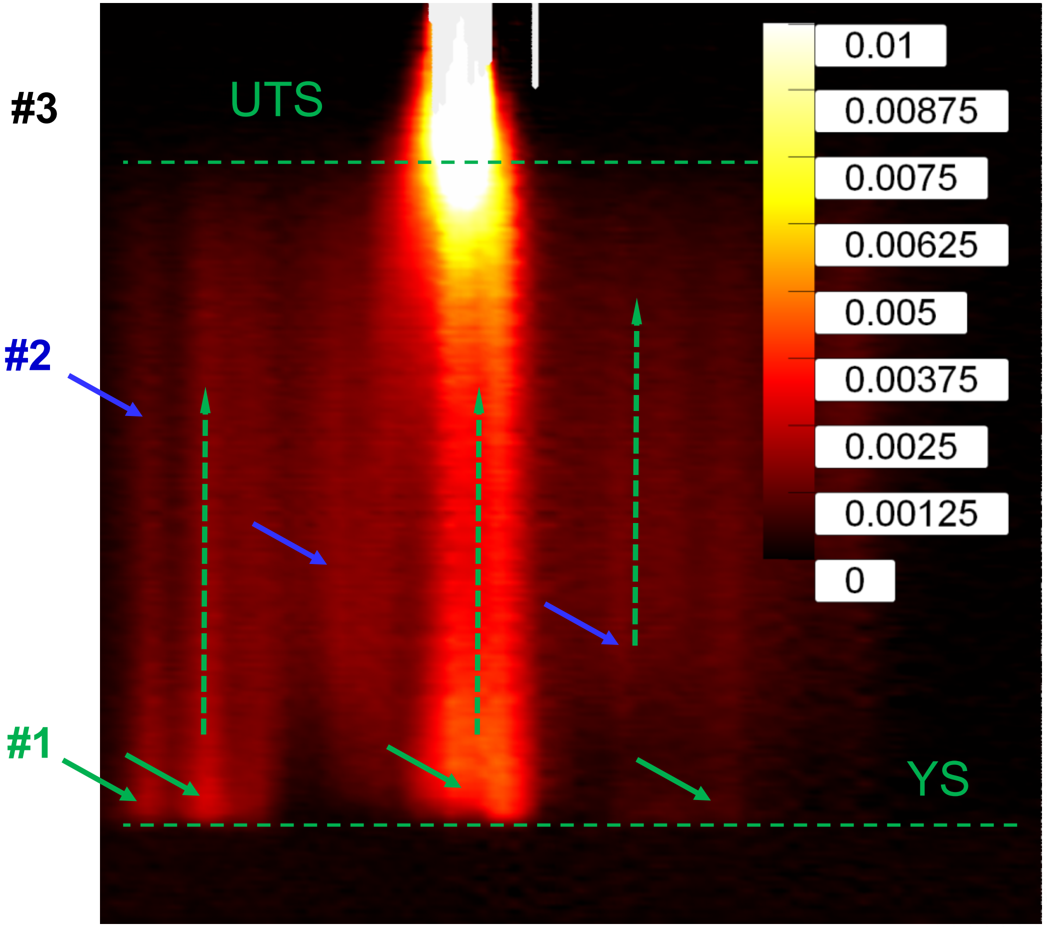
Target 8 specimens displayed localized and banded deformation behaviors

Events:

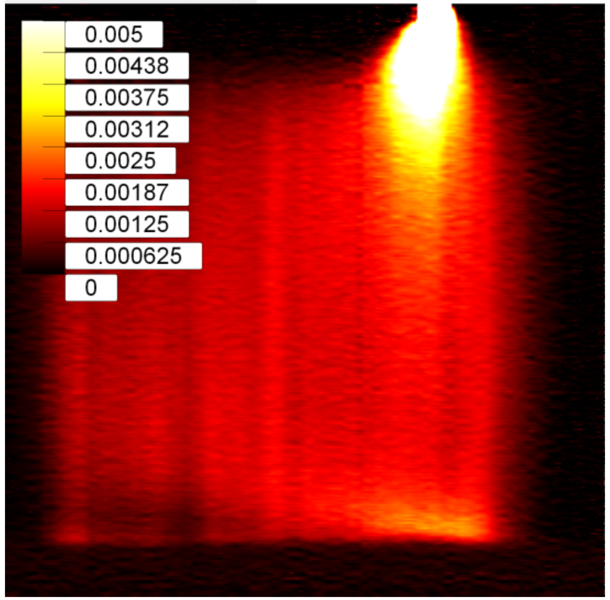
#1. Several deformation "spots" appeared immediately after YS.

#2. "Spot" activity did not remain the same during the test. Some "spots" decayed, and new became active.

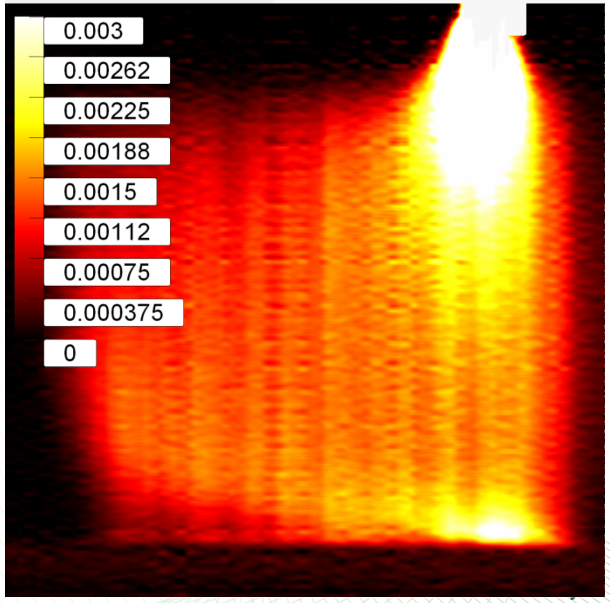
#3. At the UTS point, all active strain areas (except one) disappeared. The survived area becomes a neck.



Target 8, D6-6, TE = ~36%



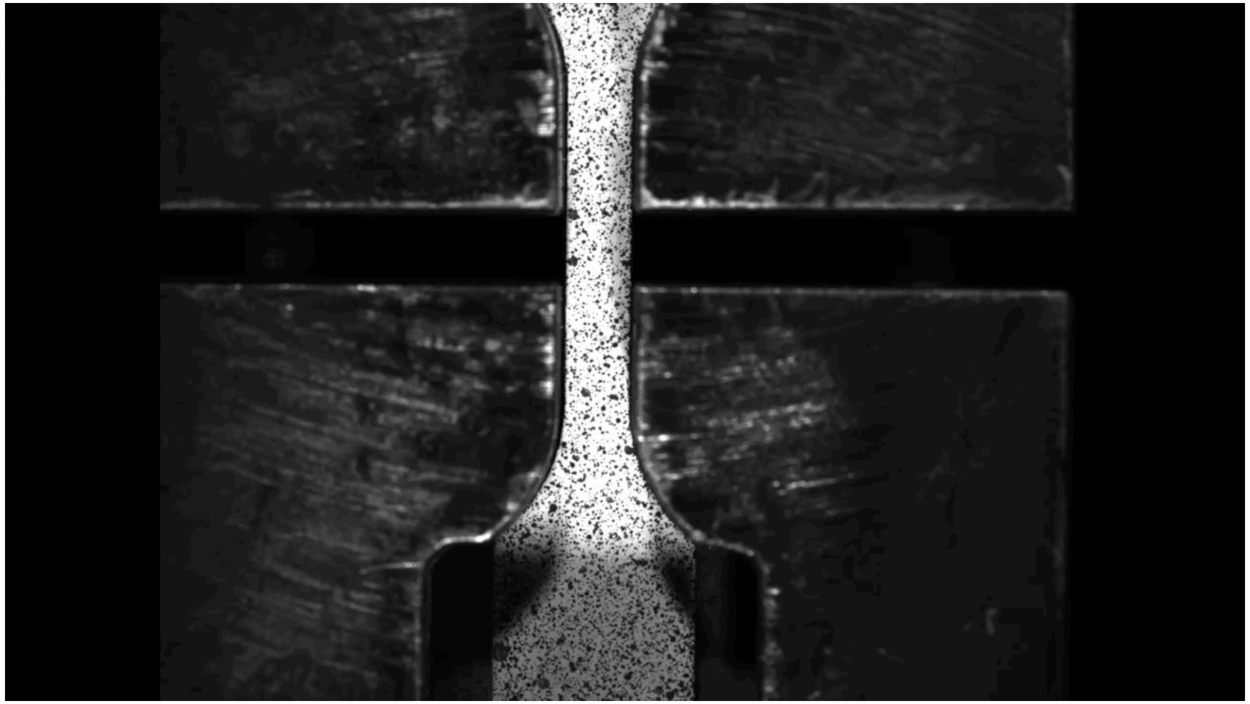
Target 8, D6-1, TE = ~39%



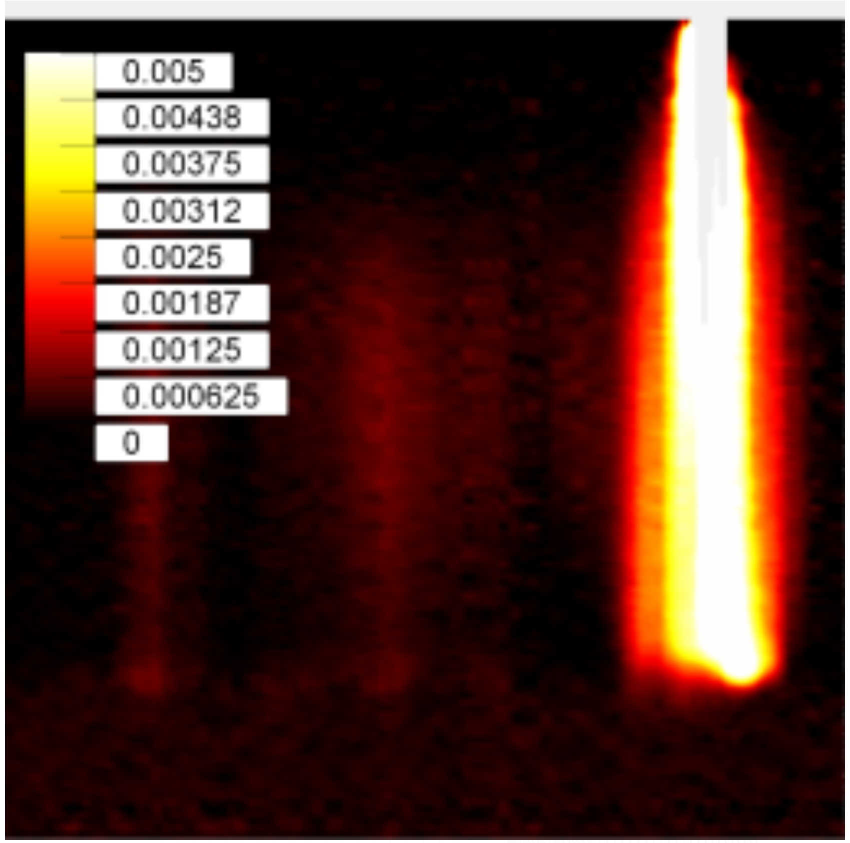
- No Luders-like band movement was observed.
- Plastic strain tended to localize in few limited areas.
- Only part of the gauge was involved in deformation resulting in TE~20-25%.

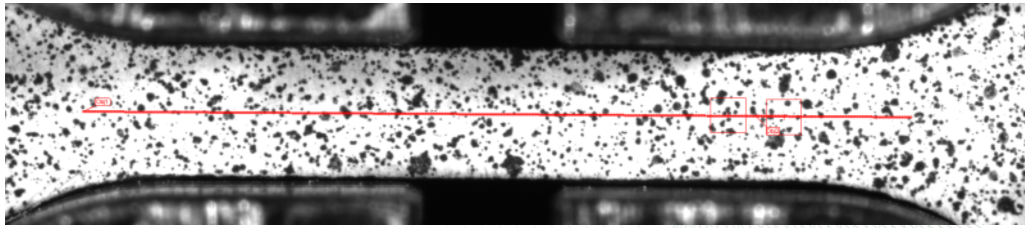
Target 8 specimens displayed highly localized deformation

- Some Target 8 specimens displayed highly localized deformation
- Significantly reduced total elongation value



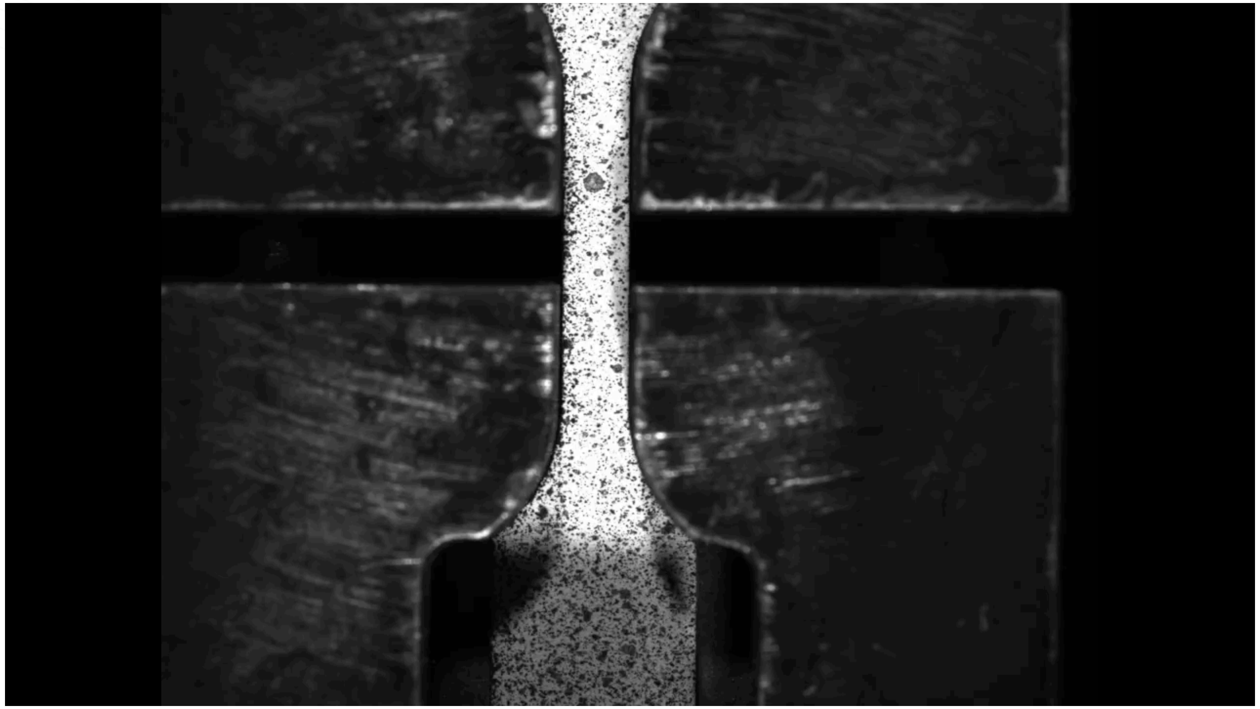
Target 8, D7-2 (5.3 dpa), TE = ~13%



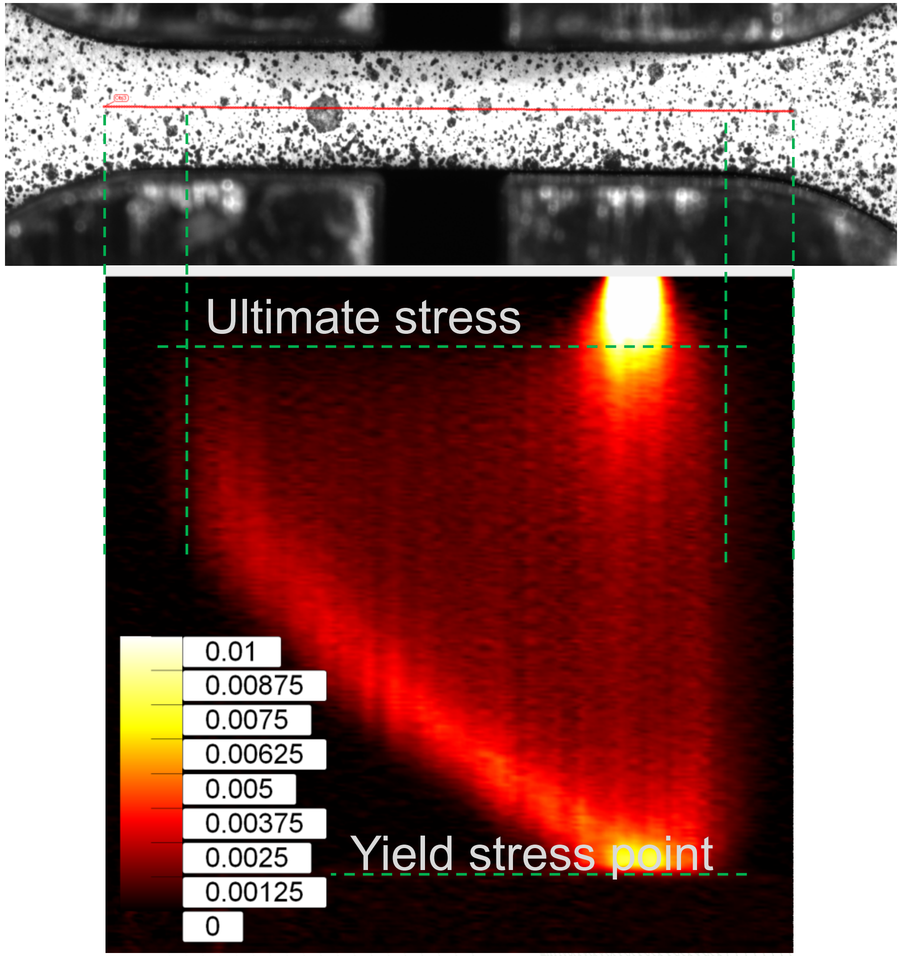


Behavior of Target 9 specimens was varied and peculiar

- Local plastic deformation was initiated at the right side of the specimens
- Strain hardening rate was high enough to stimulate Lüders band propagation along the specimen gauge section length

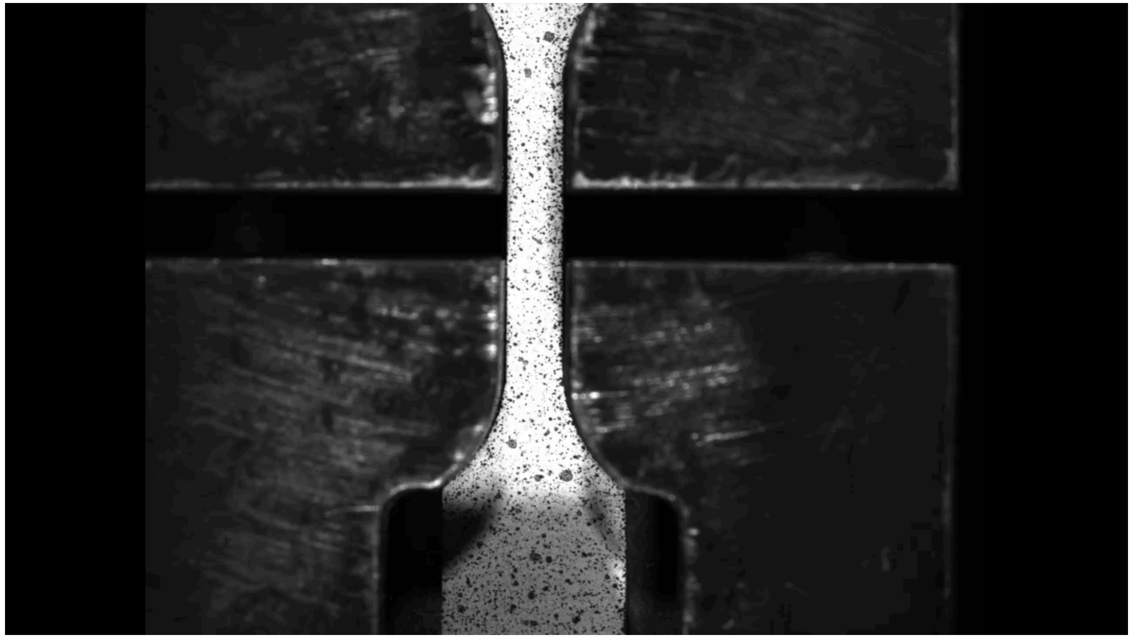


Target 9, D6-1 (6.1 dpa), TE = ~28%

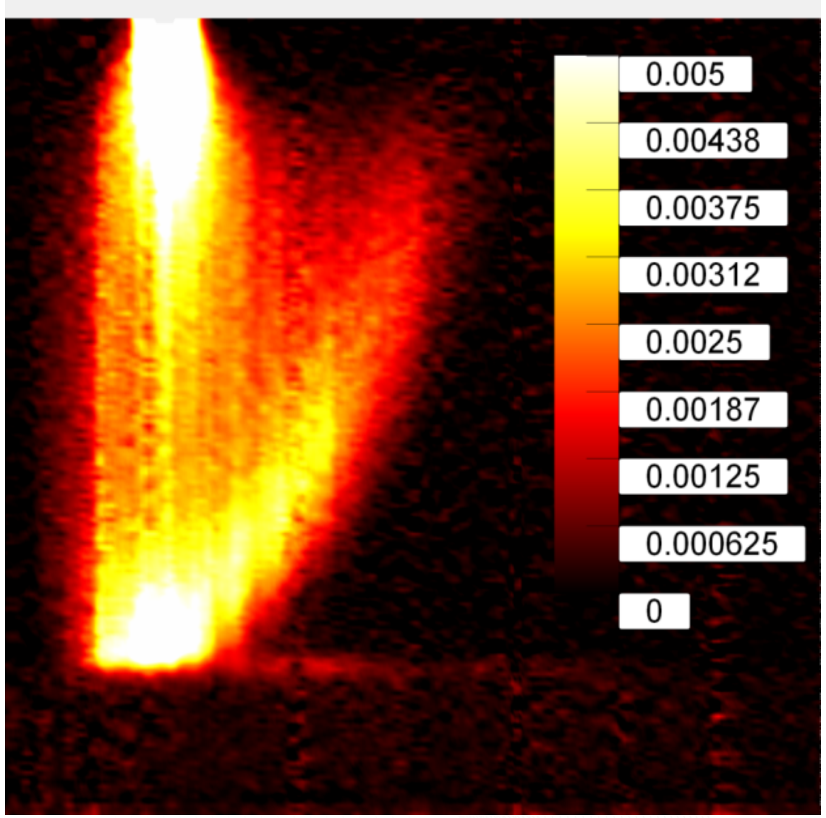


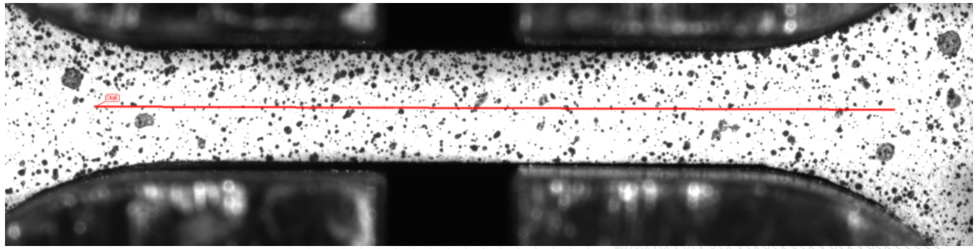
Deformation bands on some specimens only propagated across half of gauge section

- Local plastic deformation was initiated at the left side of the specimens
- However, strain hardening rate was not high enough to support Lüders band movement
- The band propagated only part of the gauge and decreased in amplitude



Target 9, D6-2 (7.0 dpa), TE = ~19%





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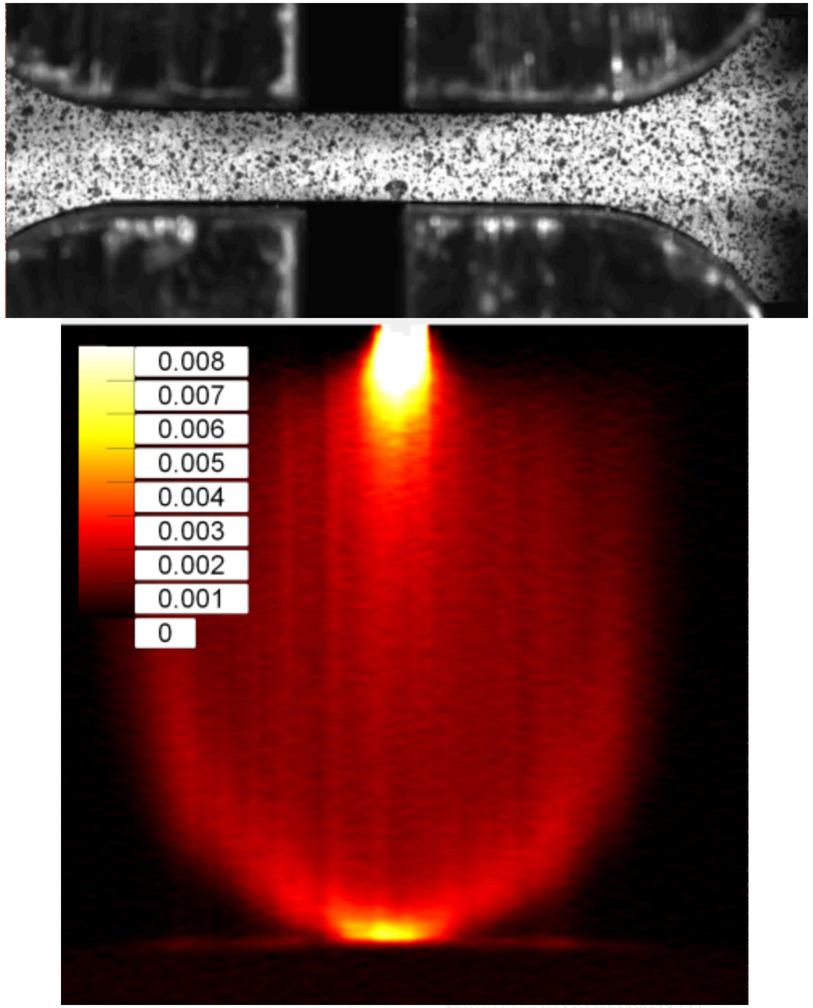
Dual deformation bands originated and terminated in center of gauge section of D7-1 from Target 9

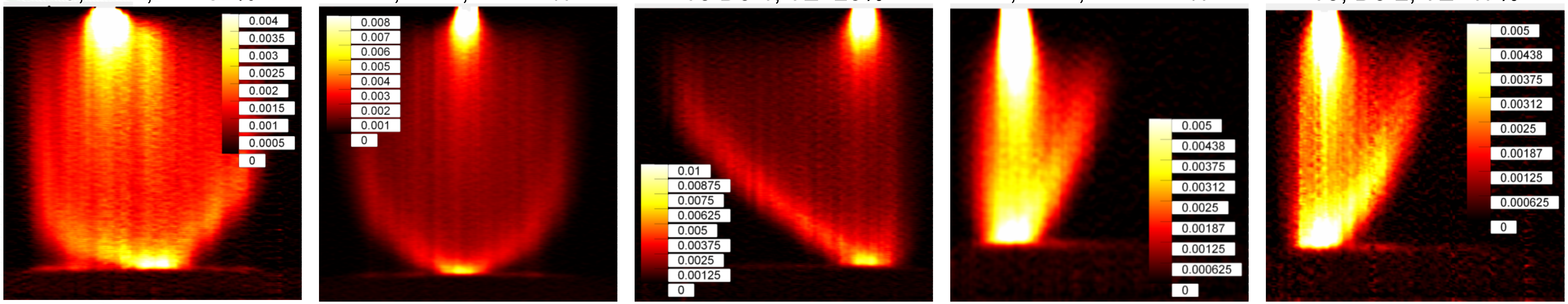
- Two deformation bands originated at the center of the gauge section
- Bands propagated outward and consumed gauge section

Target 9, D7-1 (5.8 dpa), TE = ~33%



Examples of deformation behavior of Target 9 specimens

T9, D7-4, TE=31% | T9, D7-1, TE=32% | T9 D6-1, TE=26% | T9, D6-3, TE=17.5% | T9, D6-2, TE=17%



- Several different behaviors lead to significantly different measured properties
- But “traditional” metrics don’t seem to capture the true (ductile) behavior of the material

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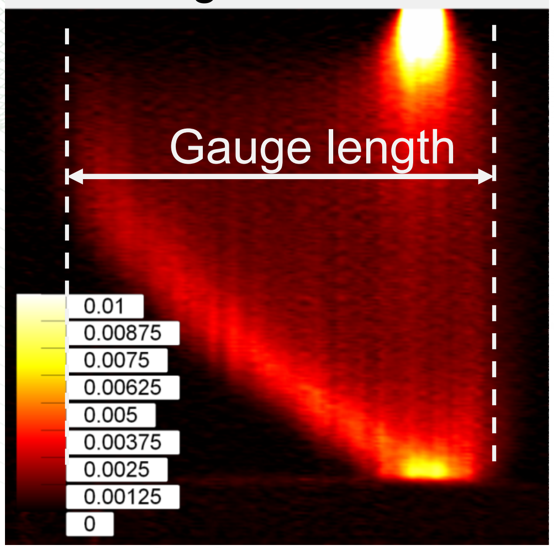
What is the best way to interpret abnormal deformation?

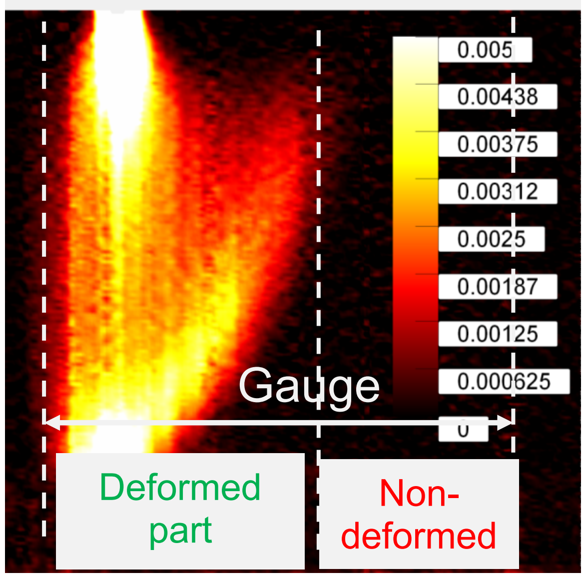
Target 9, D6-1



Band passed along all the gauge (TE~26%).

Therefore, total elongation seems to be correct.

Target 9, D6-2



Band passed only ~60% of the gauge (TE~17%).

Therefore, total elongation value appears to be underestimated.

- DIC revealed specific plastic strain distribution patterns
- For some specimens part of the gauge was not involved in deformation
- **Are we getting the an accurate measure of the actual ductility for the irradiated specimens?**
- **Is there a way to better estimate the actual ductility value?**

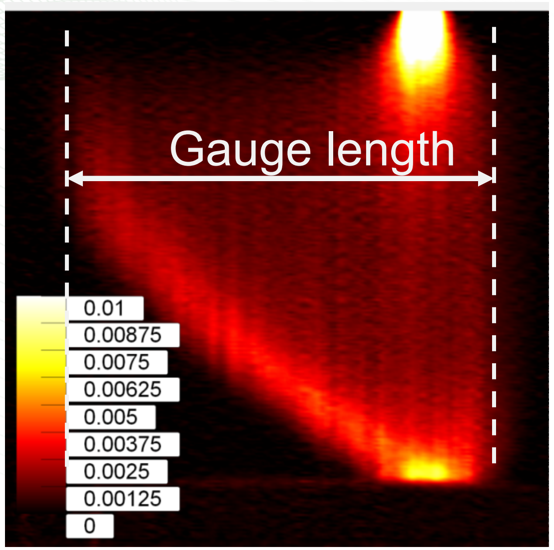
Simplified approach might be just to correct the ductility values, taking into account the non-deformed gauge length:

TE[corrected] ≈ TE [observed, 17%]* (1/0.6) ≈ 28%.

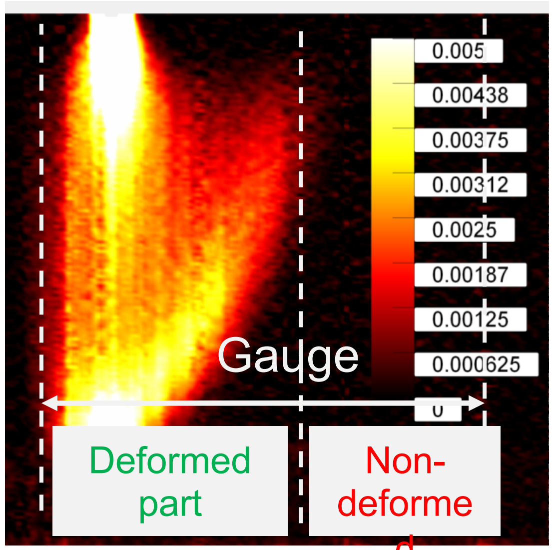
The estimated value is in good agreement with the result for fully-deformed specimens.

Estimating real ductility using expected uniform elongation

T9D6-1



T9D6-2



- The concept discussed above may be further improved by employing simple constitutive equation analysis.
- During tensile testing, necking occurs when hardening rate becomes less than acting stress:

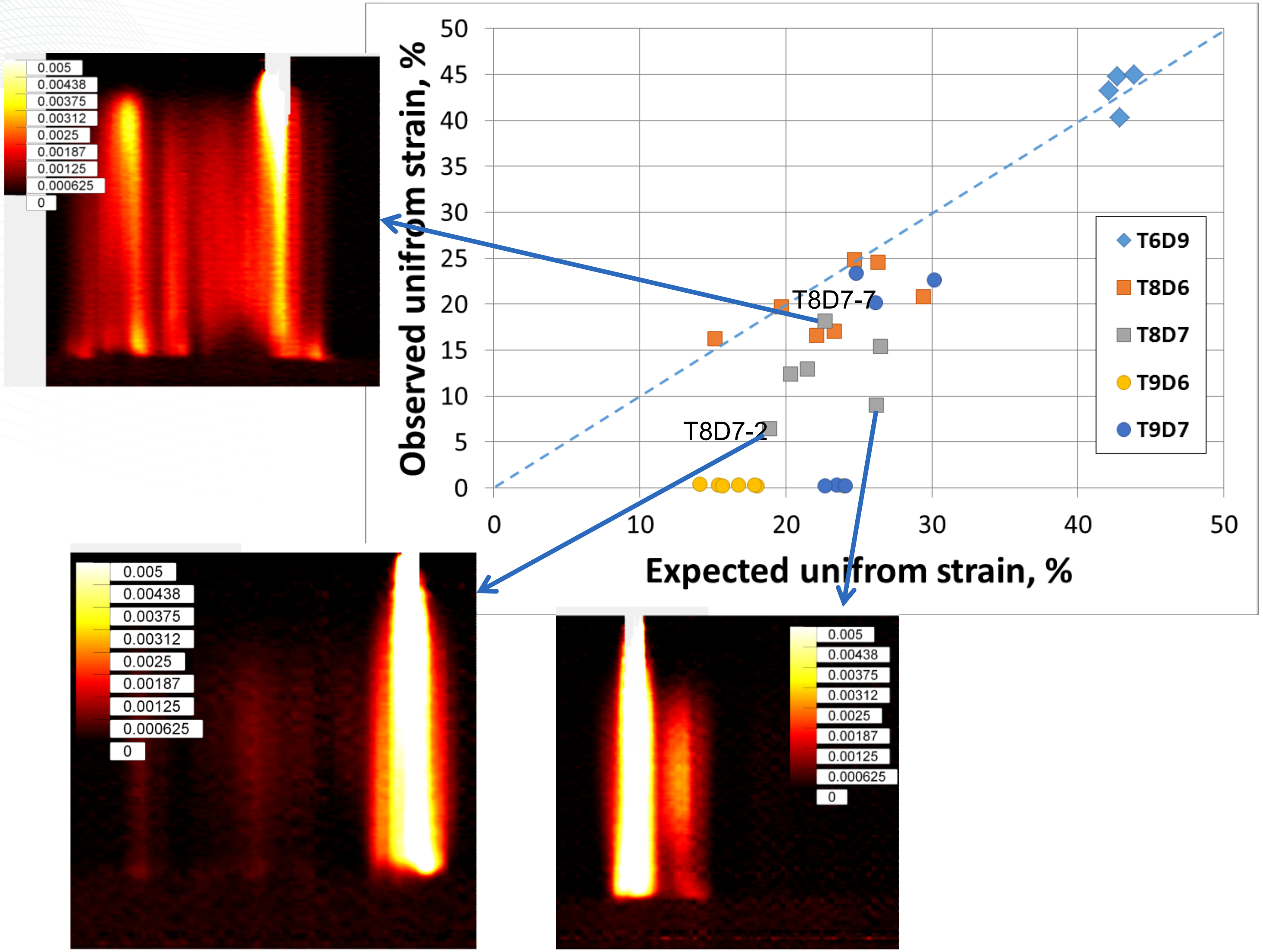
$$d\sigma/d\varepsilon \le \sigma \qquad [1]$$

- Swift equation, $\sigma = k \times (\varepsilon - \varepsilon_0)^{0.5}$ [2] provide good true stress approximation. Differentiating this equation and using [1] it is easy to show that:

$$\varepsilon_{EUD} = 0.5\ (1 - 2\varepsilon_0).$$

- ε_{EUD} (expected uniform deformation) may be easy estimated using DIC-obtained true stress – true strain curves.

Expected vs. observed uniform ductility



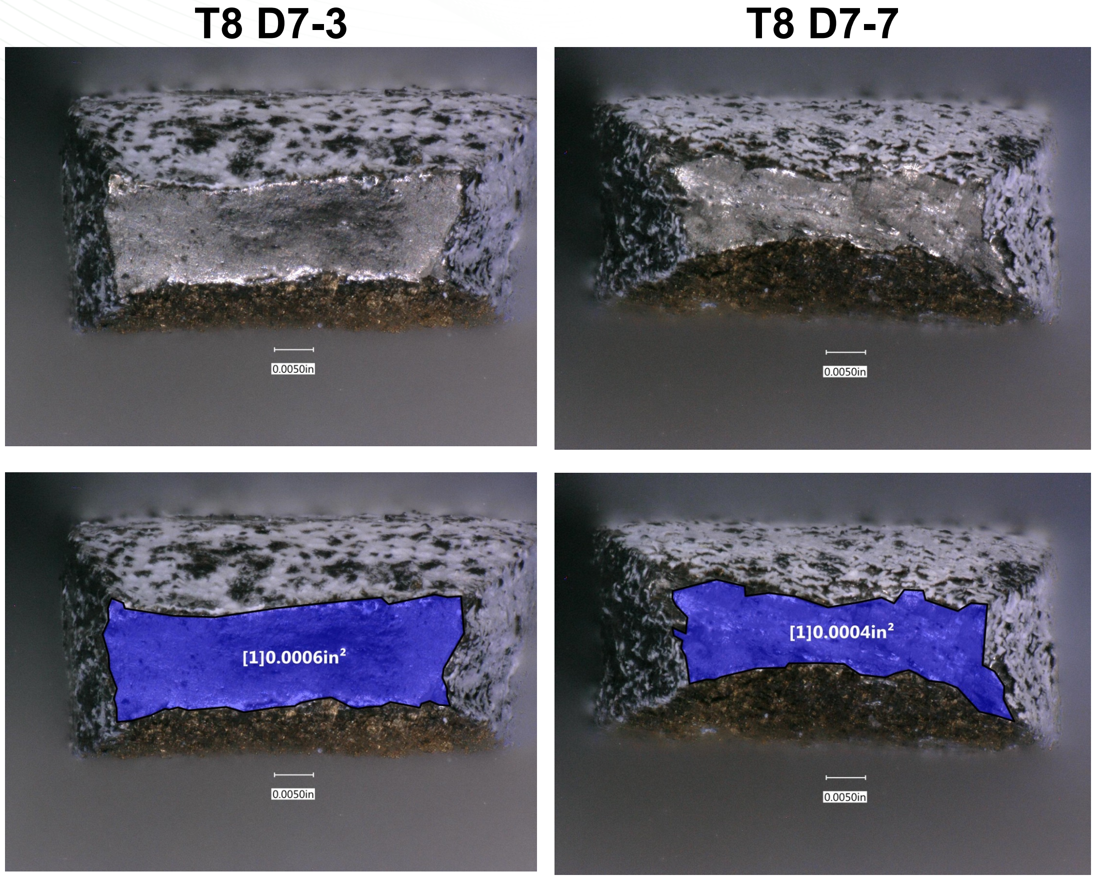
Experimental and calculated uniform elongation (UE) values were compared for the tested specimens.

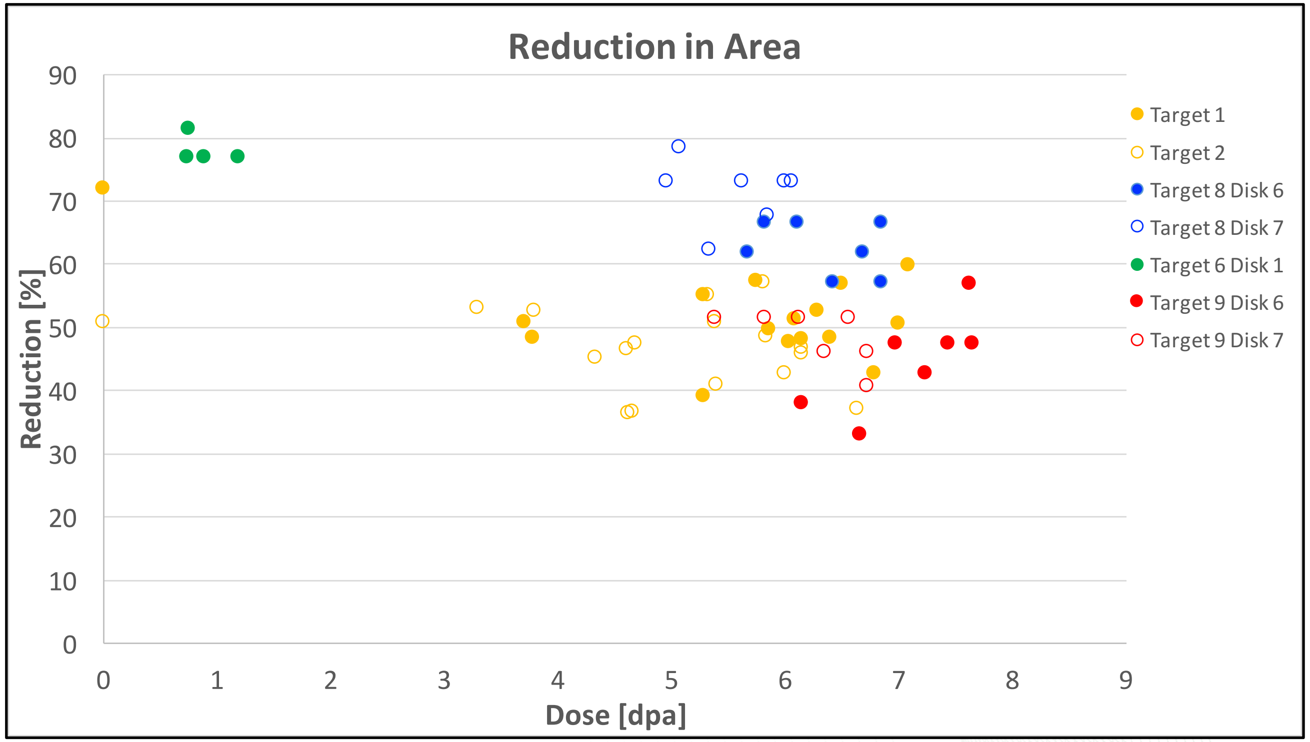
One may see the low-dose (T6D9) specimens demonstrated good agreement between the expected and experimental UE values.

At the same time many specimens showed much smaller UE compared to the expected ones.

Reduction in area might be a better indicator of ductility instead of elongation

- Final area was measured for all specimens after testing using digital image analysis





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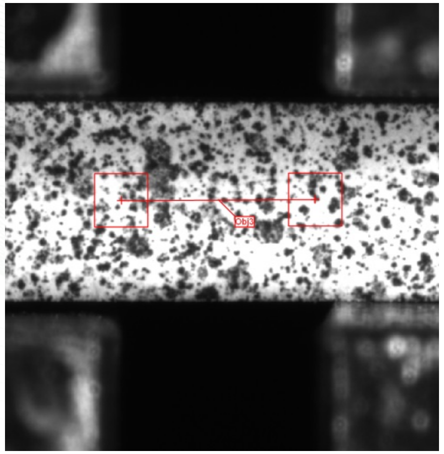
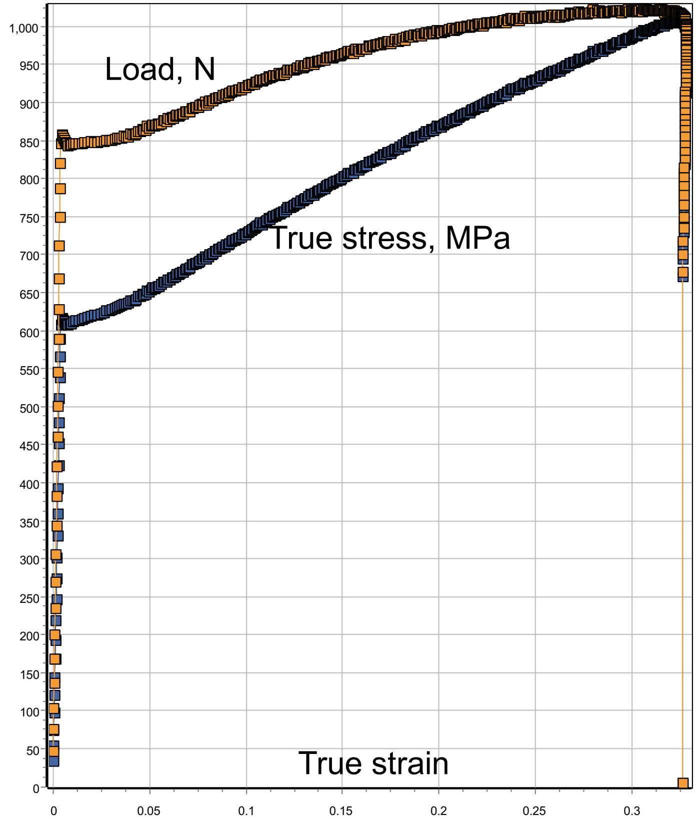
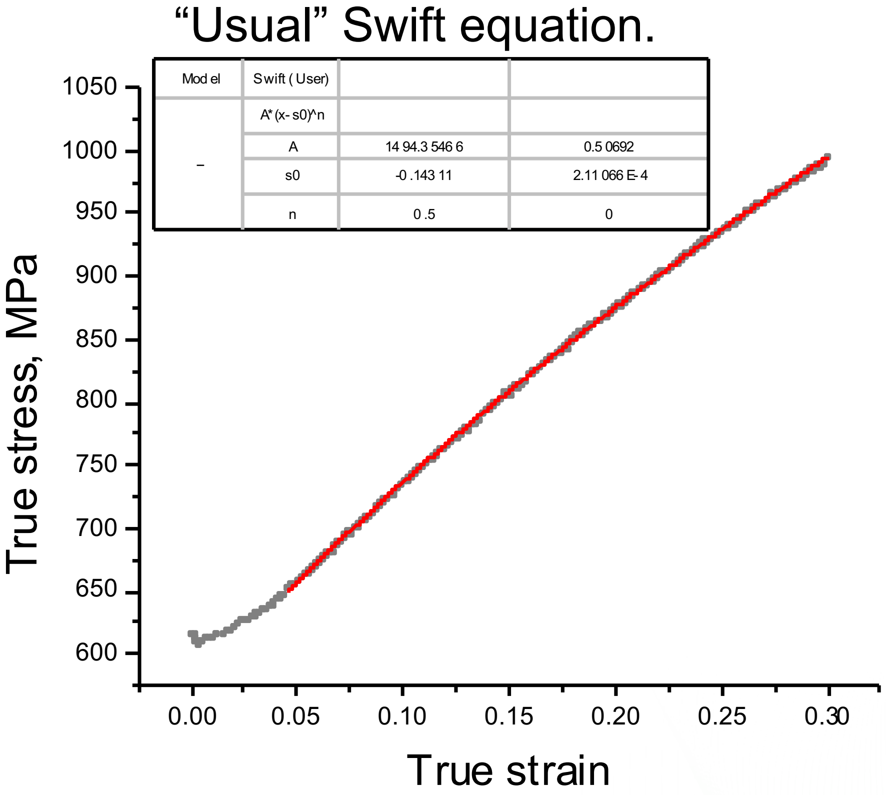
Summary

- 32 tensile specimens were fabricated and tested from SNS Targets 6, 8, and 9
- Results show 316L retained appreciable ductility (18-24% TE) for doses up to ~7.6 dpa
- Digital Image Correlation analysis showed non-uniform deformation occurred in several specimens
  - For some specimens, only a fraction of the gauge section participated in plastic deformation
- DIC results suggest typical elongation values (UE, TE, and RA) do not appear to accurately reflect the true ductility
  - A more accurate metric is needed

Strain hardening behavior (T6D1_1)



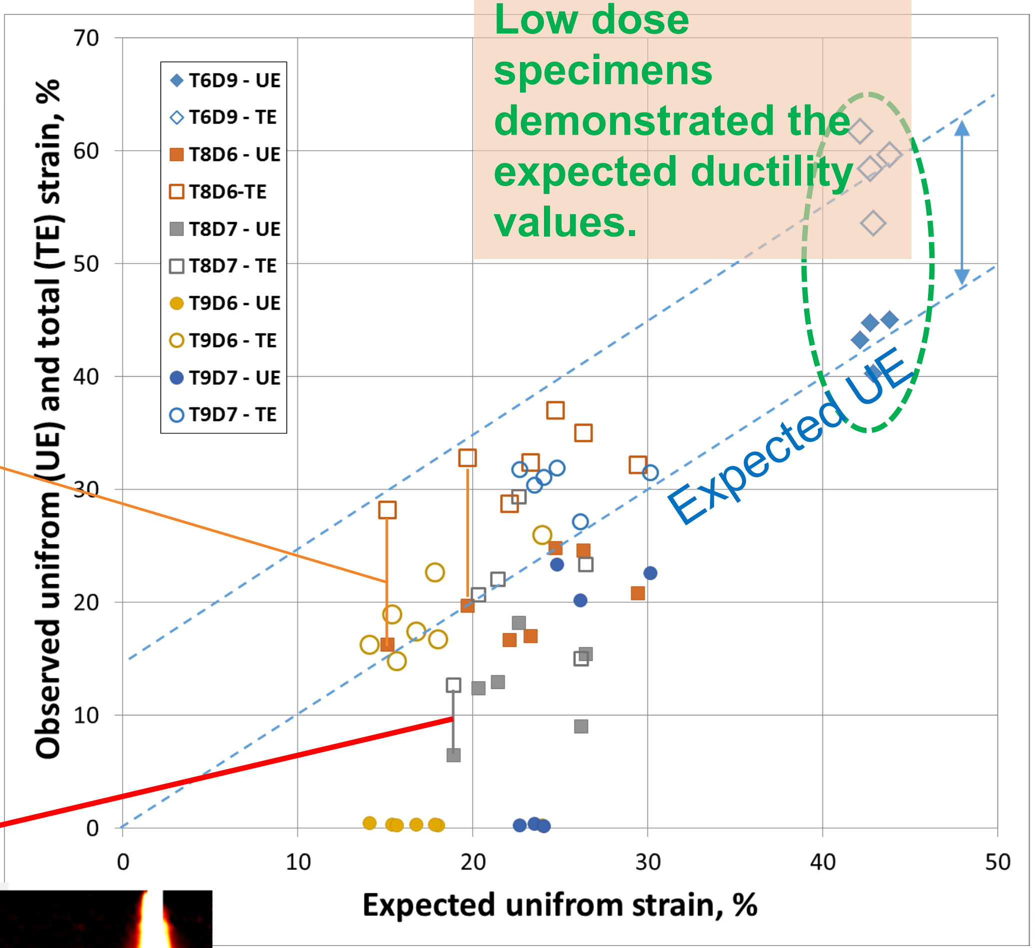




True stress–true strain curves may be calculated for all specimens.

The curves reflect real (acting) plastic deformation behavior and strain hardening.

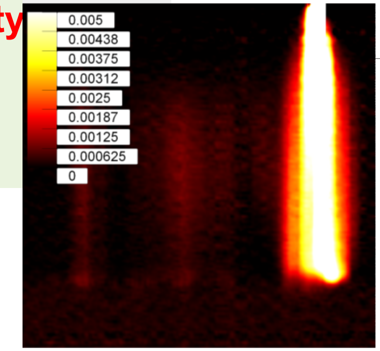
Expected vs. observed ductility



Low dose specimens demonstrated the expected ductility values.

Some irradiated specimens fully realized the ductility resource

However, many objects showed very small ductility due to the early strain localization.



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