High Heat Flux Exposures of Tungsten and Novel Tungsten Alloys for Plasma Facing Components

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1 PennState Applied Research Laboratory

2 editekk Innovating materials one atom at a time

3 Commonwealth Fusion Systems

INFUSE Innovation Network for Fusion Energy

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Outline

- Intro to high heat flux (HHF) and experimental setup at Applied Research Lab (ARL) @ Penn State University
- Thermal Shock Testing: W and W Heavy Alloy (WHA)
  - Completed INFUSE project
- Thermal Shock Testing: W and dispersion strengthened W alloy
  - Ongoing INFUSE project
- Conclusions

Why Tungsten for Fusion Plasma Facing Components (PFCs)?

Pros

- Highest melting point of pure metals
- Low Sputtering yield
- Low Tritium retention

Cons

- Core plasma contamination leads to radiative collapse
  - Core W concentrations of 10^{-4} – 10^{-5}
  - Cracking and UFO's
  - Melting and droplet ejection
- Brittle material at room temperature
  - Difficult to machine
- Grain growth and morphology changes under heat and particle loads
  - Blistering, He bubbles, W fuzz

Y Uedo, Fus. Eng. Des. **89**(7—8) (2014) 901-906

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Need for new W materials and manufacturing technologies

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Electron Beam HHF testing facility

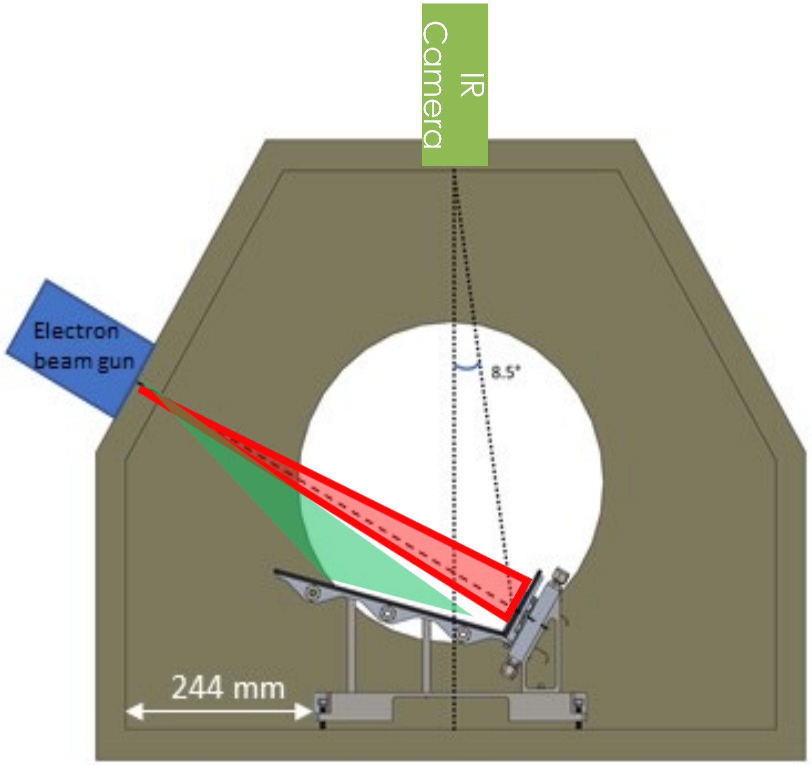
PennState
Applied Research Laboratory

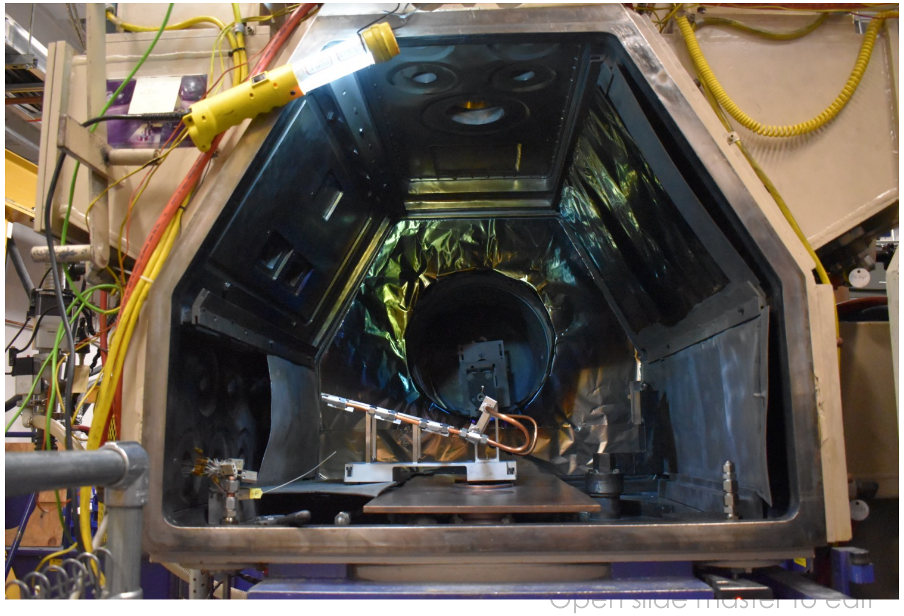
Extreme Environment Electron Beam High Heat Flux Testing and Evaluation Capabilities – Ryan L. Romesberg, Penn State ARL

ARL Electron Beam Facility

- ARL Electron Beam:
  - 2 A, 17 kV electron beam
  - Focus from 1 – 10 mm FWHM
  - Target peak heat fluxes: 100-500 MW/m^2
  - Target heat flux factors: 40-100 MW ·s$^{0.5}$/m^2
  - High end limit for ELMs, lower limits for disruptions

- Diagnostics:
  - FLIR SC4000 IR camera (30-400 Hz)
  - Video camera (60 Hz)
  - TC's and RTD's on rear of test articles

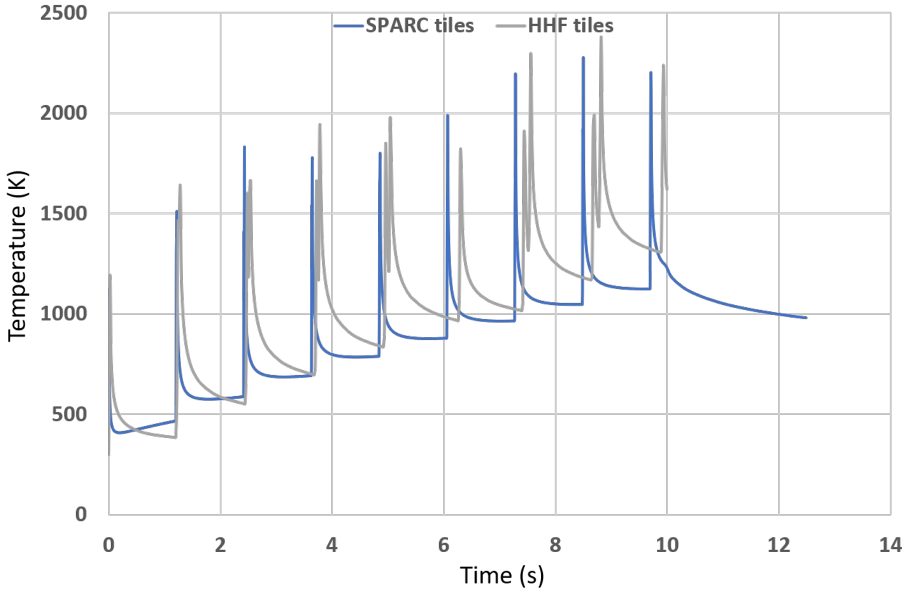


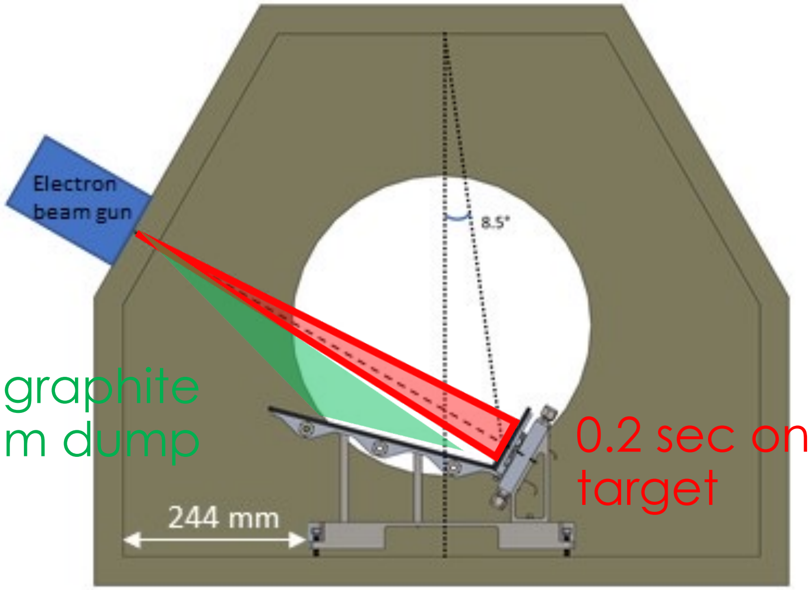


E-beam mimicking strike point sweep

Beam Dump

Target





0.8 sec on graphite beam dump

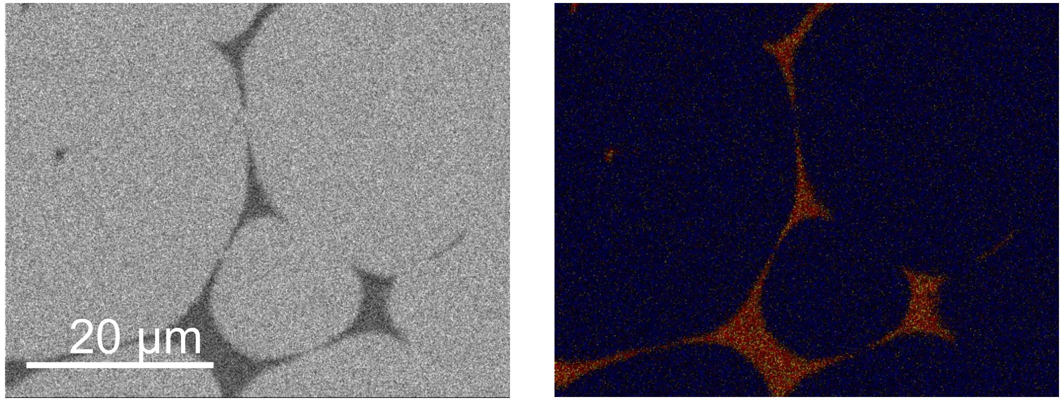
0.2 sec on target

W & W Heavy Alloy Thermal Shock Testing

Commonwealth Fusion Systems

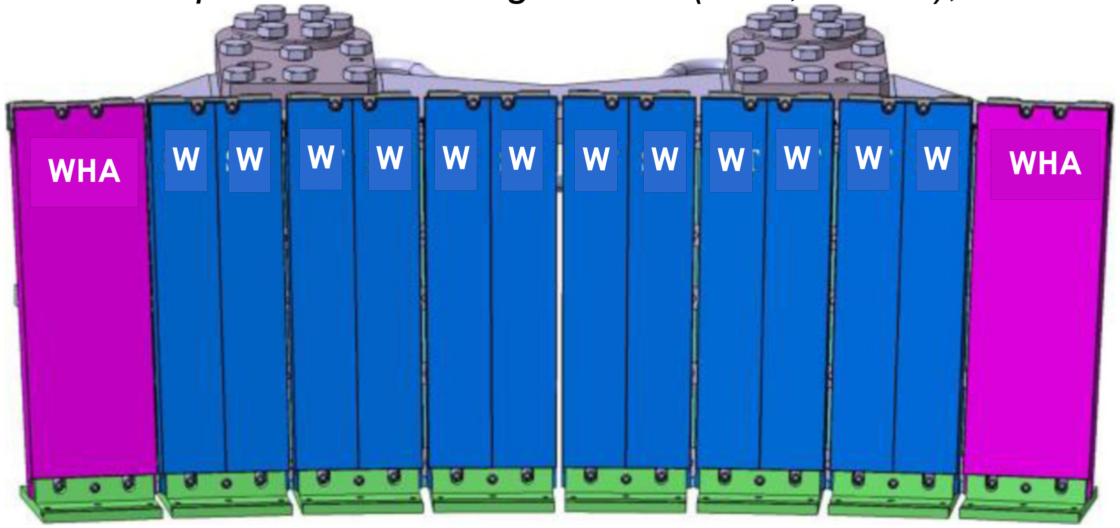
Tungsten Heavy Alloy (WHA) for fusion applications

- Sintered W powder with Fe and Ni binder
  - Not an alloy but a mixed metal composite
  - ASTM B777 Class 4 – 97% W, 2% Ni, 1% Fe
  - XRF measurements across multiple surfaces saw W fractions of 95-98%, Ni/Fe ratios of 1.1-1.9



Overlap of an EDS image – W-L (Blue, 95.8%); Fe-K

- WHA Tiles tested for AUG [1-4]
  - Cyclic testing at GLADIS up to 20 MW/m^2
  - Installed in the divertor for 2017 AUG campaign

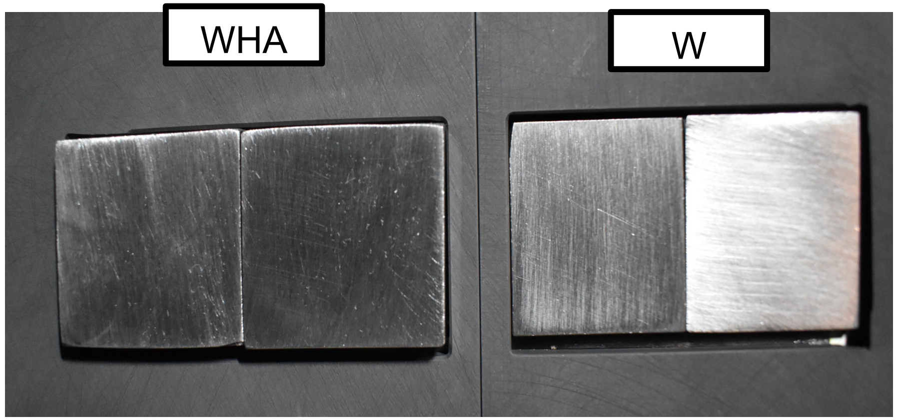


- Advantages of being ductile at room temperature
  - Improved machineability
  - Cheaper than pure W
  - Crack resistant for low temperature disruptions and optical hot spots [5]

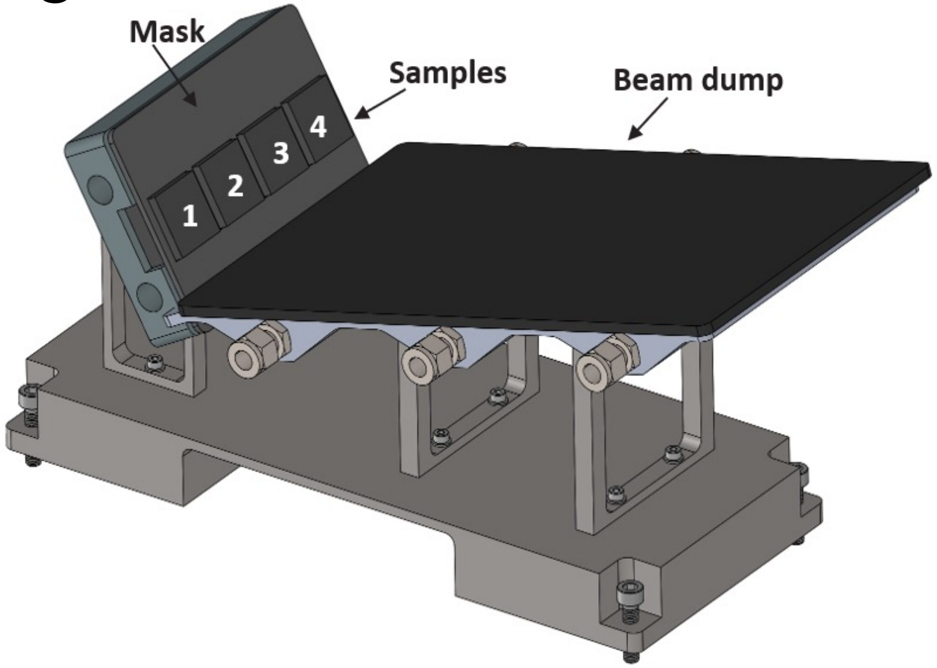
[1] Neu R., et al., *Fusion Engineering and Design* 124 (2017): 450-454.
[2] Neu R., et al., *Journal of Nuclear Materials* 511 (2018): 567-573.
[3] Maier H., et al., *Nuclear Materials and Energy* 18 (2019): 245-249.
[4] Maier H., et al., *Nuclear Fusion* 60.12 (2020): 126044.
[5] Diez M., et al., *Nuclear Fusion* 60.5 (2020): 054001.

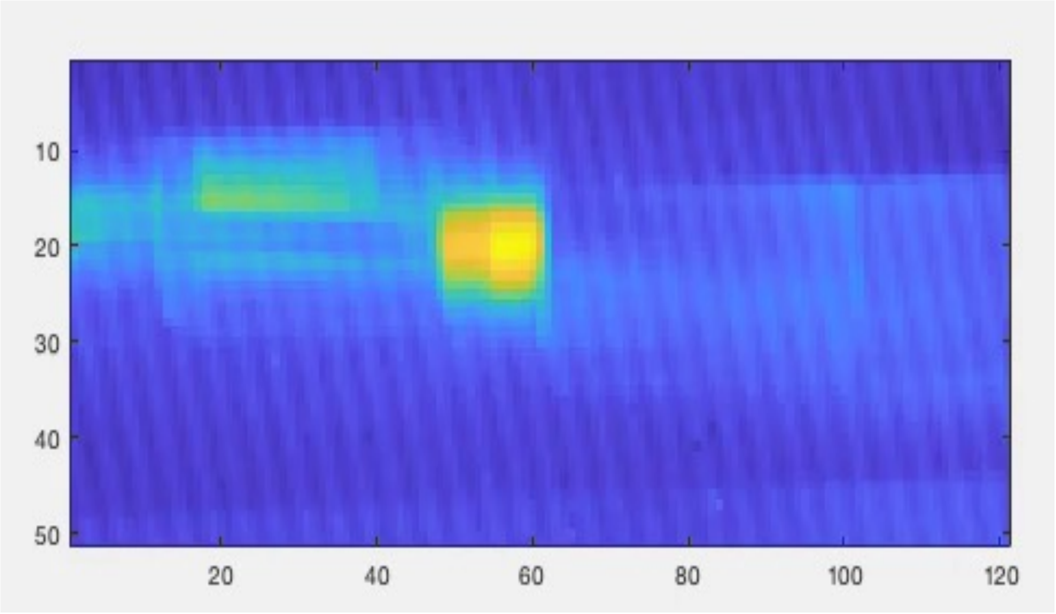
Desire to test to failure at SPARC relevant conditions

- Side-by-side comparison of WHA (Elmet ET97) and pure W tiles (hot rolled)



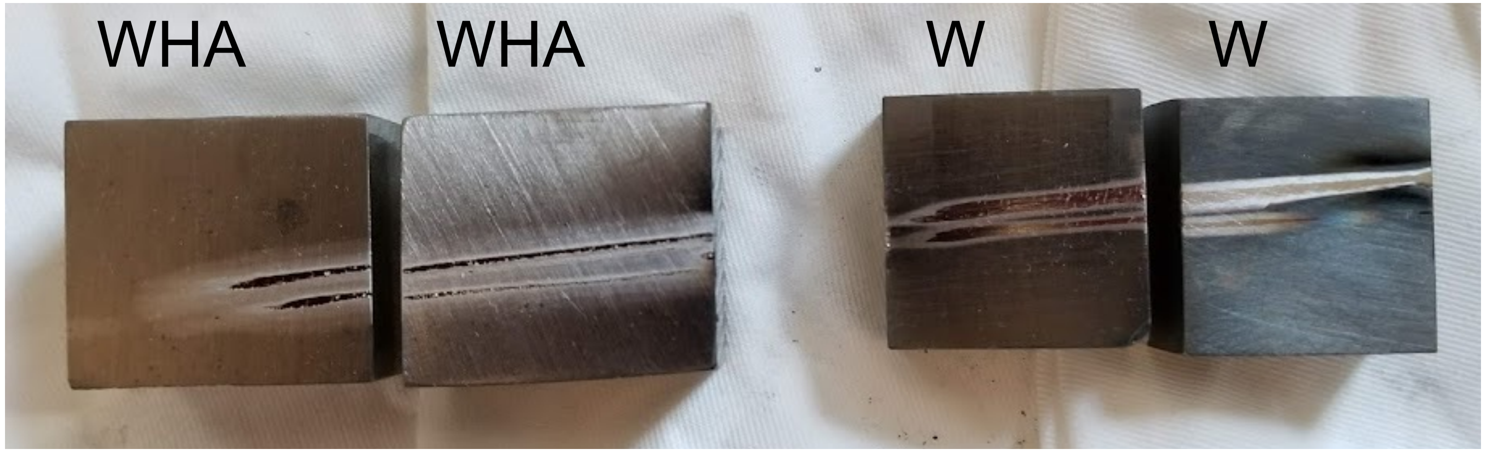
- W and WHA test articles are unconstrained
  - Only stresses are generated by thermal gradient





Flash heating of surface shows similar melt behavior

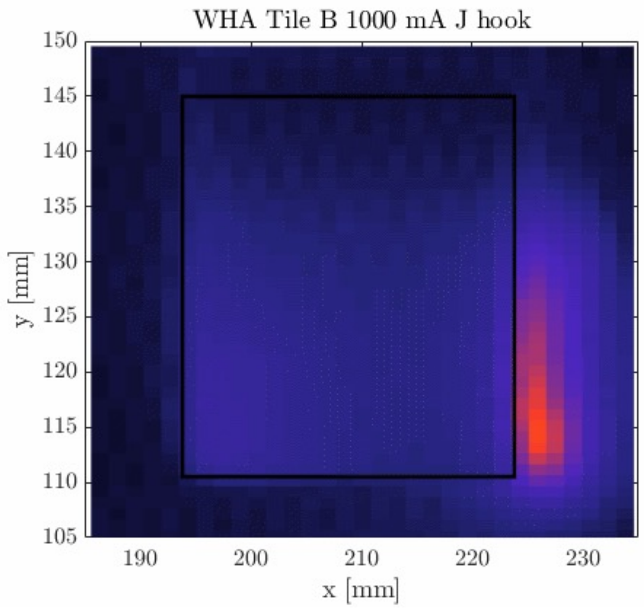
- Estimated peak heat flux of ~500 MW/m^2 and a beam velocity of 120 mm/s with a FWHM of ~3 mm.
- Suggest that flash melting due to disruptions should not result in any adverse difference in the behavior between the two materials.
- Consistent with previous work using plasma shock exposures*

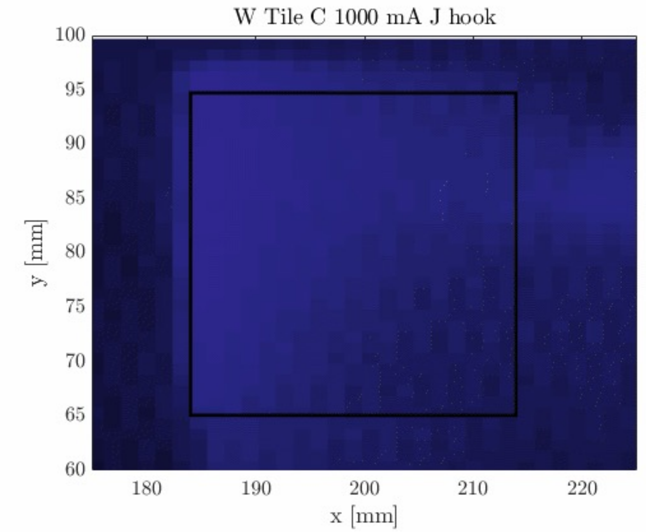


*Laas T., et al., *Fusion Engineering and Design* 151 (2020): 111408.

Slower beam with a lower average heat flux

- Same beam shape but slower sweep speed and reduced I_{beam}
  - 48 mm/s in the x-direction.
- Average peak of ~100 MW/m^2





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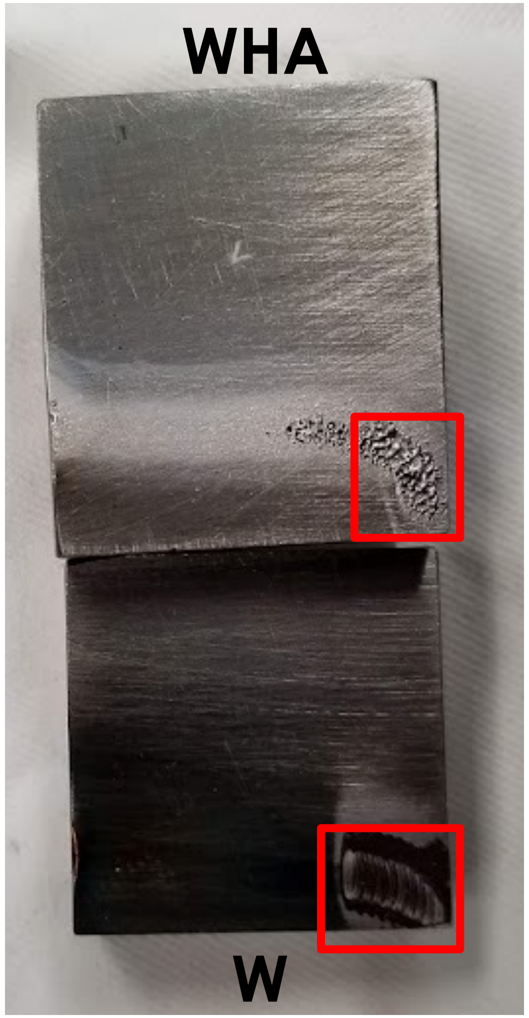
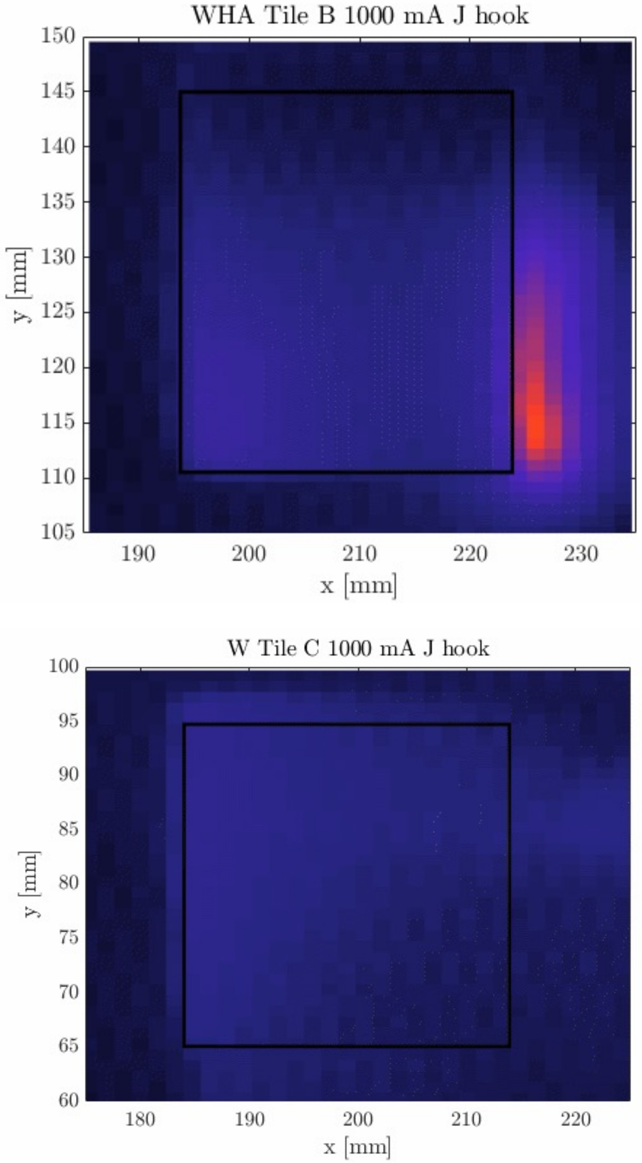
- First pass:
  - No surface melting of the W.
  - Surface roughing of the WHA





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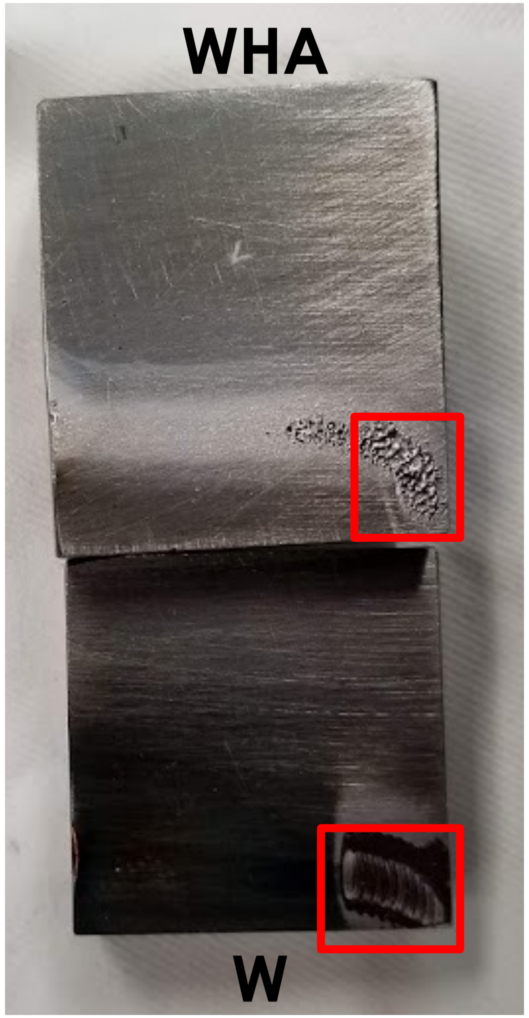
- Second pass:
  - Surface temperatures exceed tungsten melt temperatures.



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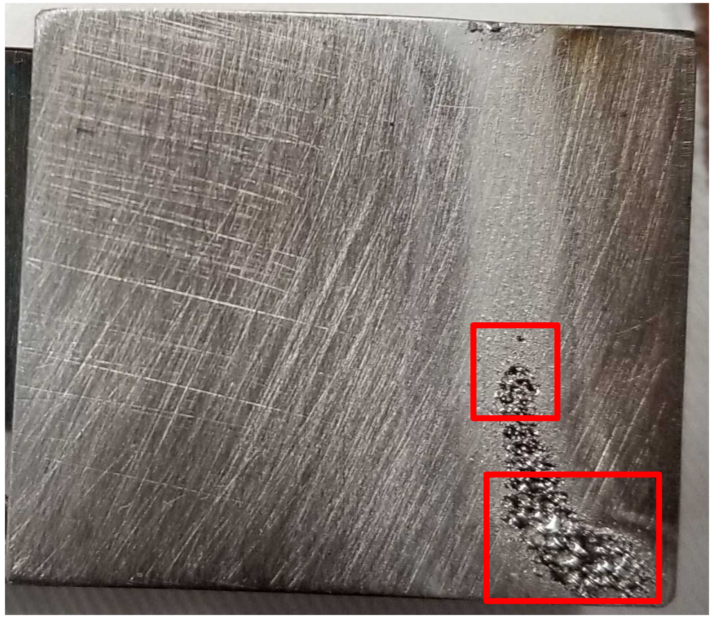
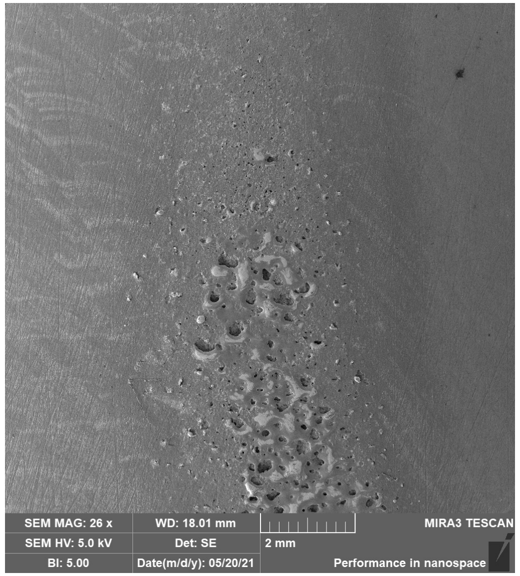
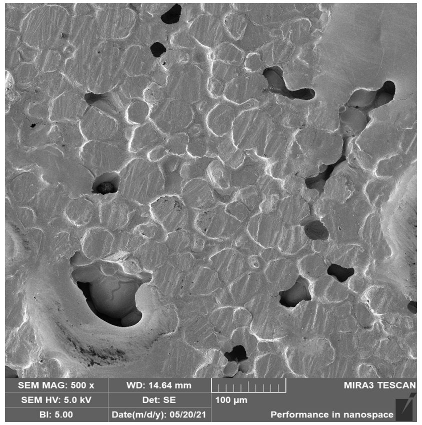
Failure mechanism of the W and WHA differ

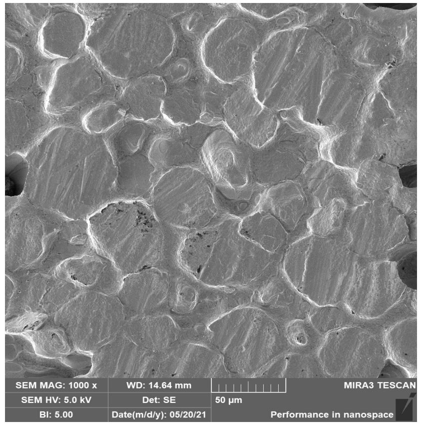
WHA







500x

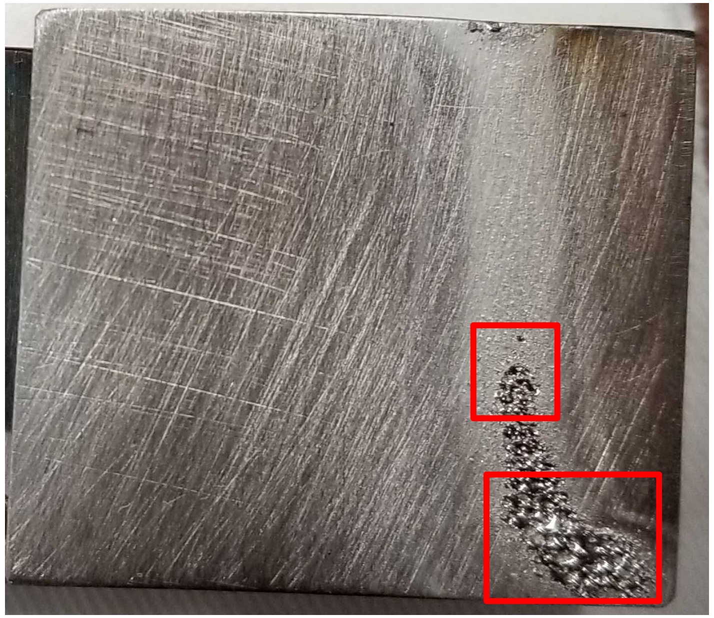


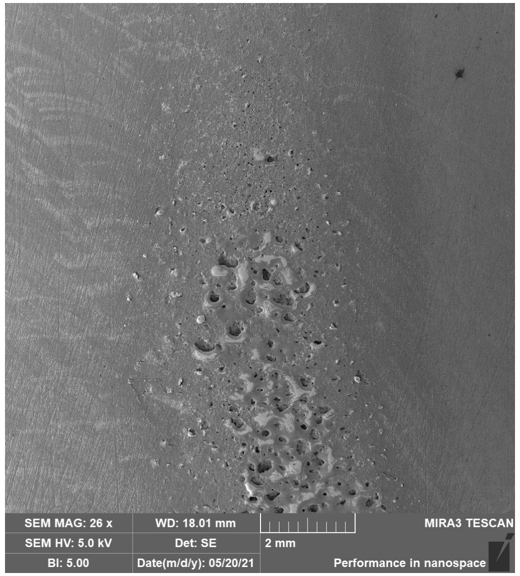
1000x

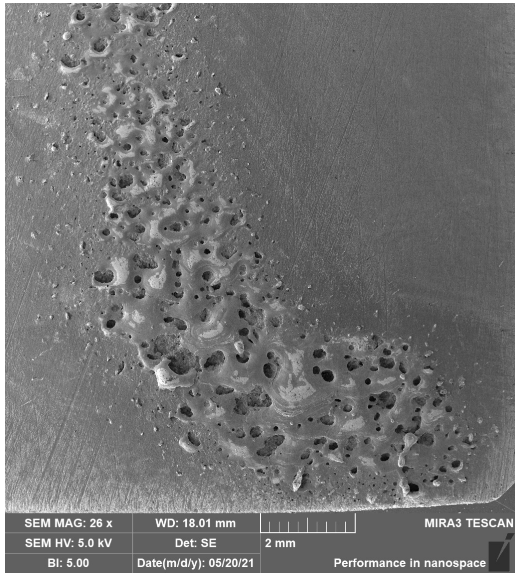
- Some signs of increased Fe/Ni but within the range of the pre-test.
- Etched surface exposing W particles.
- ‘Craters’ left from the ejection of W grains
- Similar to overloaded case by Neu et al. [Neu, et al., JNM **511** (2018) 567-573]

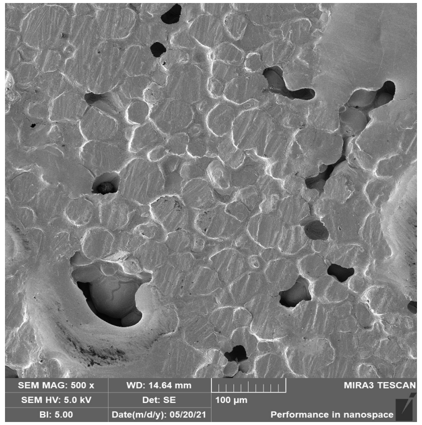
Failure mechanism of the W and WHA materials differ

WHA









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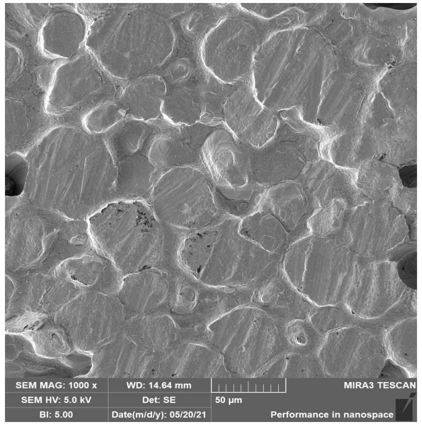

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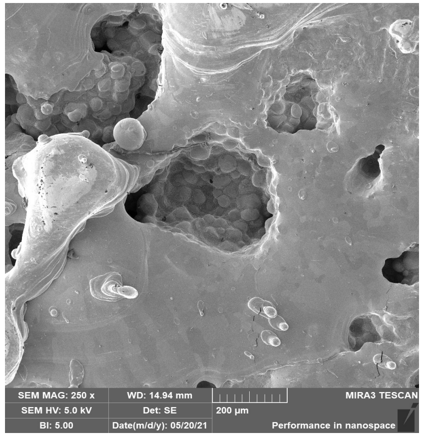
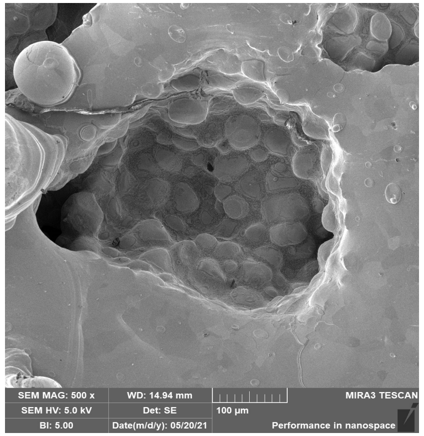
- Surface melt regions are saturated with tungsten.



250x



500x

Impact on SPARC PFC material choices

- Enhanced failure mechanism for WHA has been identified relative to pure W, occurs at temperatures higher than tungsten recrystallization but lower than tungsten melt.
- As a result the decision was made for SPARC PFCs to keep high heat flux regions as pure W - outer limiters and the divertor target tiles
- WHA is will be used in low heat flux regions of the device as a plasma facing component accounting for ~75% of the in-vessel coverage.
  - This simplifies design resulting in more complex shapes and larger components
  - Reduces procurement and manufacturing cost

W & dispersion strengthened W Alloy Thermal Shock Testing

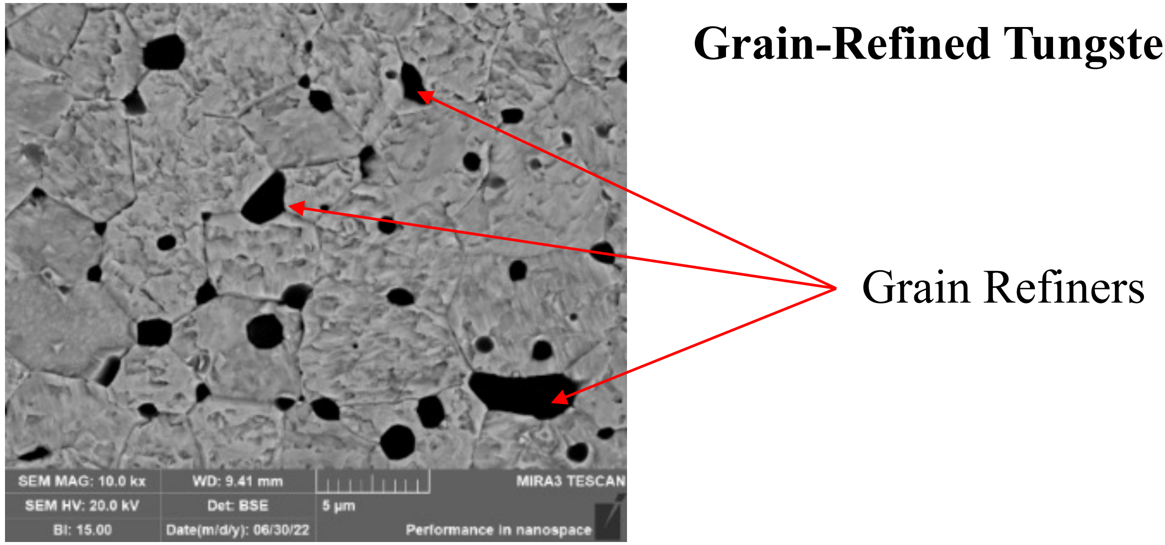
Materials Synthesis, Scalable Manufacturing, Extreme Environment Testing, and Performance Evaluation Capabilities , Christopher DeSalle - Penn State ARL

Mechanical Characterization of PFC Candidate Fine-Grain Dispersion-Strengthened Tungsten Materials, Zak Koyn - Edditek

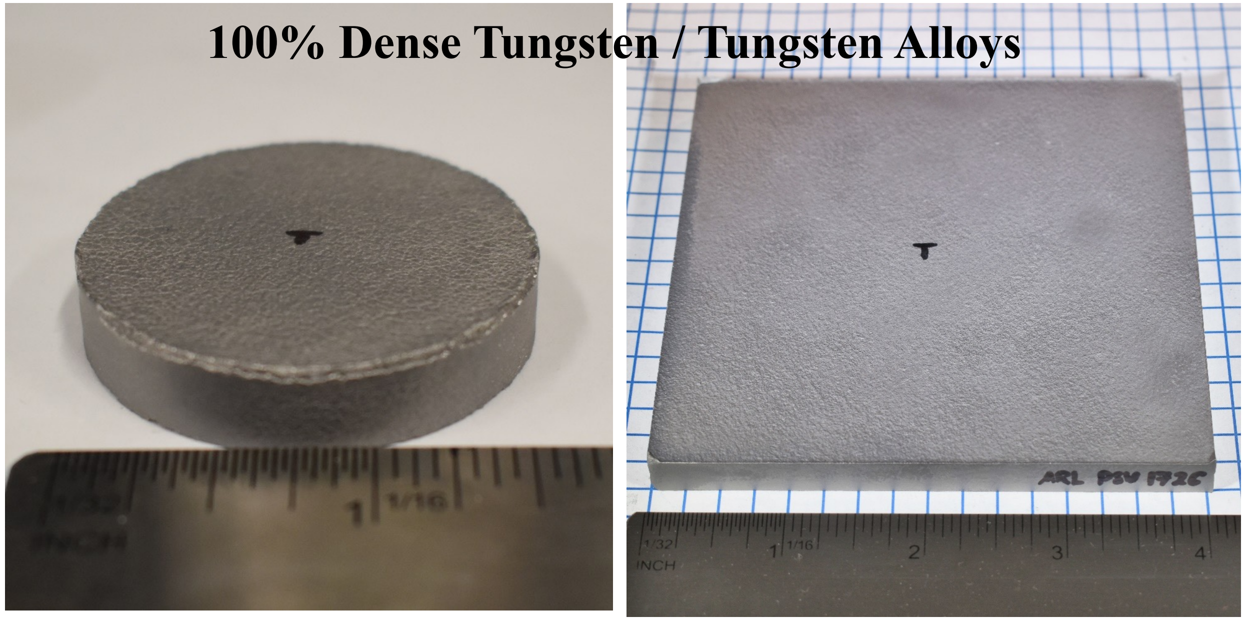
Grain-Refined Refractory Alloy Components

- Additive Manufacturing (AM) of refractory alloys produces components with large grains
  - Reducing mechanical properties
  - resistance to thermal shock
  - cracking during processing
- Goal is to reduce average grain size of refractory alloys using grain refiners
  - ceramic particles imbedded within the tungsten matrix

Grain-Refined Tungsten



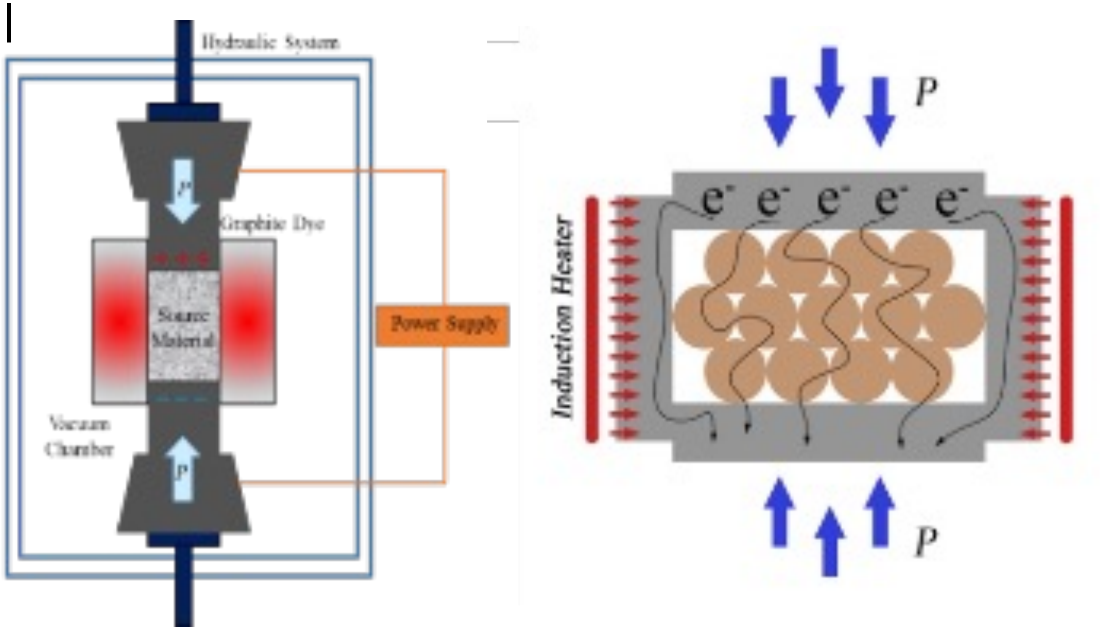
100% Dense Tungsten / Tungsten Alloys



Field-Assisted Sintering Technology (FAST) Process

- Direct Joule heating (DC) of material during sintering
  - Allows high heating rates and low process time
  - Lower sintering temperature than conventional methods
    - ROI in cost and energy
  - Accelerated processing cycle times
- Allows for multi-material and compositionally graded structures
- Joining of dissimilar materials (metal and ceramics)

Schematic of FAST Process



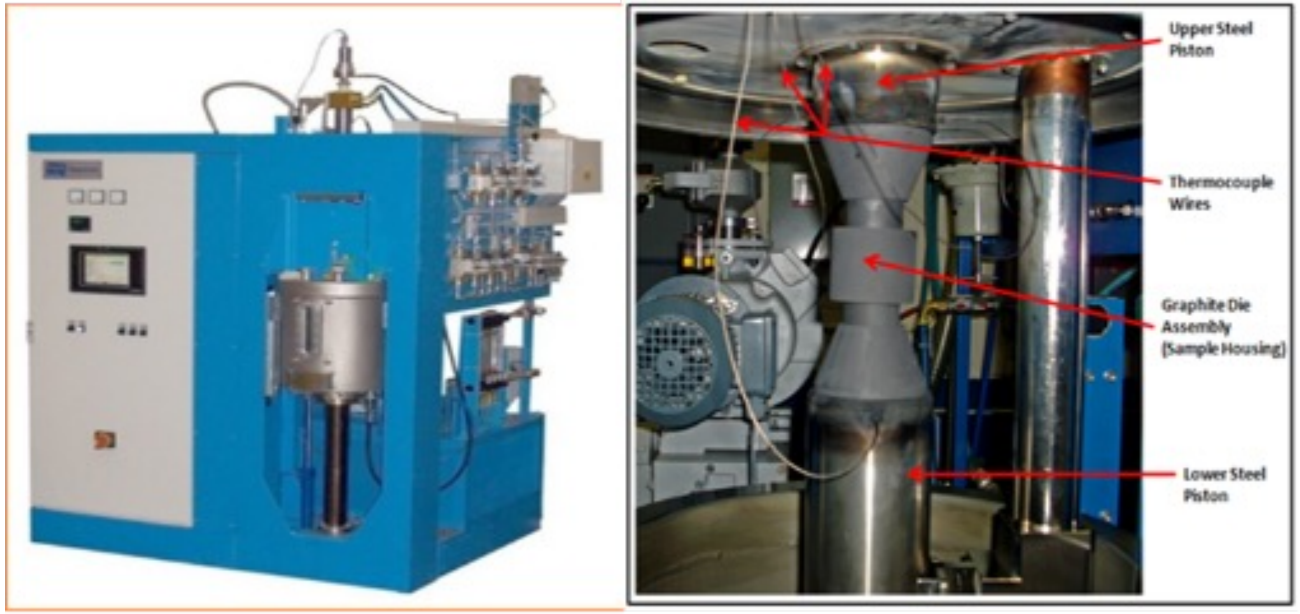
Ability to process:

- Polymers
- Metals (Al, Cu, Ti, Ni, Ta, W) and composites/alloys
- Ceramics (carbides, nitrides, oxides)

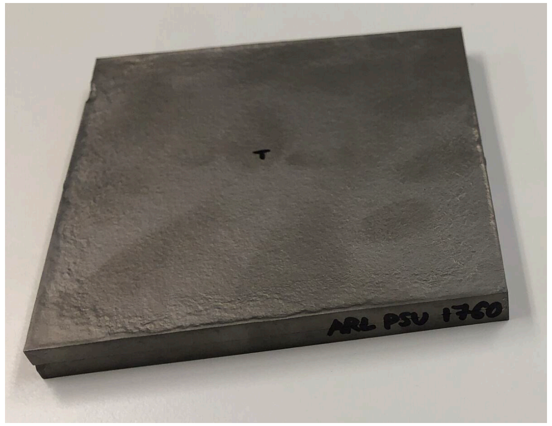
FAST W Samples produced for HHF Testing

- Produce pure W and W + ZrC samples using 25 Ton FAST system
  - Samples were EDM from graphite dye
  - 18mm x 18mm x 10mm samples cut (EDM) from larger material
    - Also removes outer carbide layer

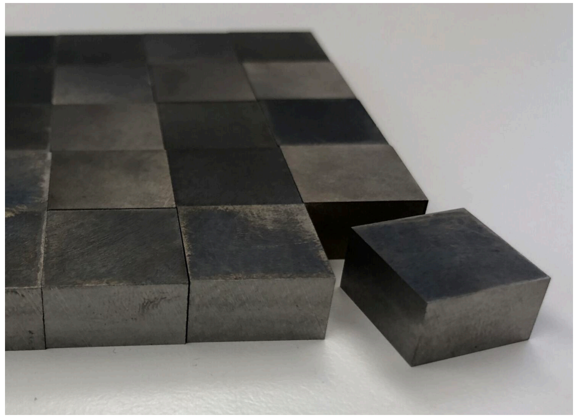
R&D FAST Unit. Max load: **25 Ton;** Maximum diameter = **80 mm**



80mm x 80mm



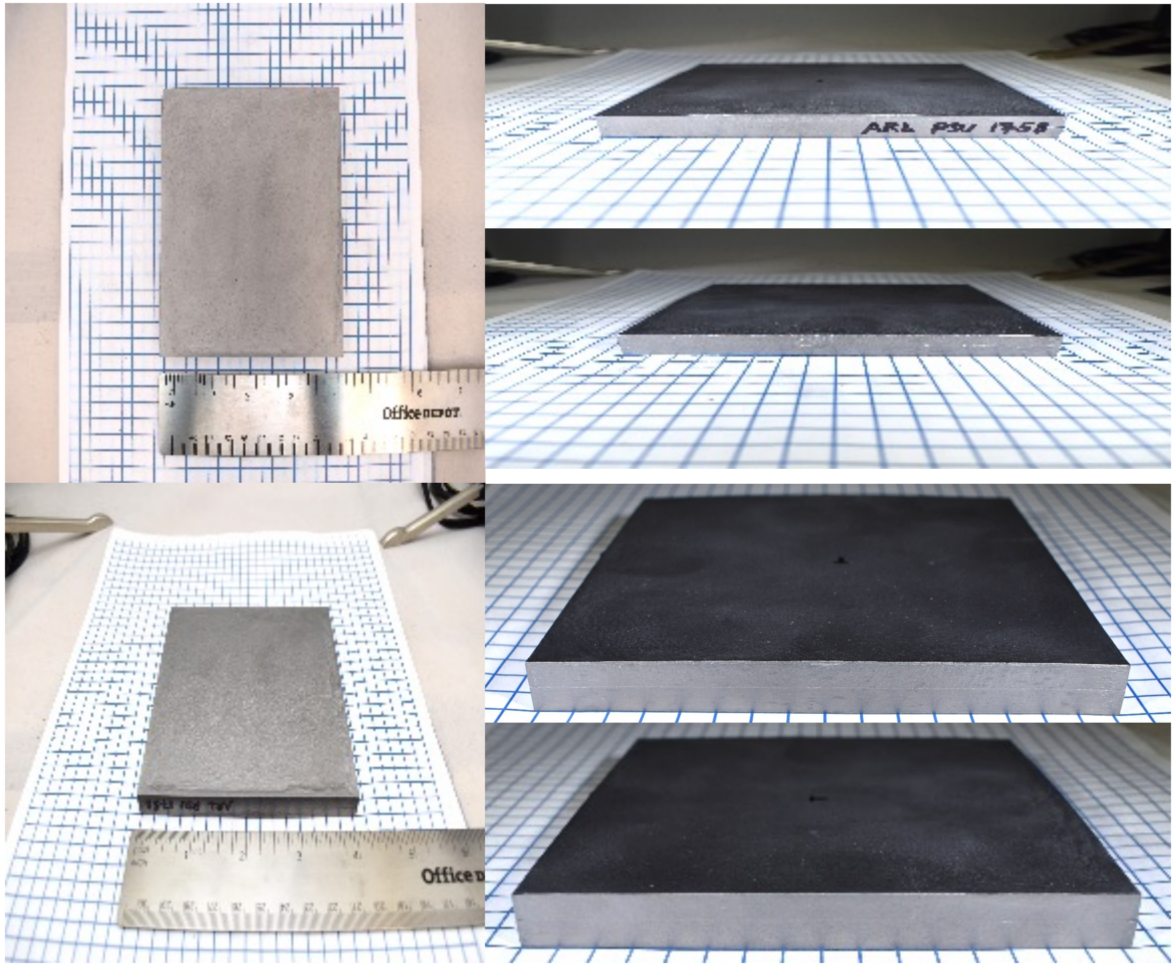
18mm x 18mm x 10 mm



Initial results

- Successfully demonstrated grain refiners in reducing the average grain size of sintered tungsten components
- This has resulting in improved thermomechanical properties
- Initial HHF Exposures conducted last week
  - ITER-grade W, pure FAST W and FAST W + ZrC
  - More testing soon!

Joining of 2, 10mm thick plates together



Joining bondline between tungsten slabs not readily observed post metallography

Summary

- HHF testing of materials is vital for developing reactor-relevant PFCs

- Electron beam based HHF tests are a cost effective and timely method of material testing
  - Relative to testing in confinement devices

- Had a direct impact on PFC material choices for SPARC

- Using HHF to test novel W materials and manufacturing techniques

Go see the posters!

- Materials Synthesis, Scalable Manufacturing, Extreme Environment Testing, and Performance Evaluation Capabilities , Christopher DeSalle - Penn State ARL

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