High Heat Flux Testing of PFCs for SPARC

3rd Annual INFUSE Workshop

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High Heat Flux (HHF) Programmatic Goals

SPARC

- SPARC is a short-pulse (10 s), high power density tokamak to demonstrate net fusion energy
- baseline divertor operation is to sweep the strike point over inertially cooled divertor (>100 MW/m^2 divertor surface heat flux)
- INFUSE project aims to
  1. Inform the divertor plasma-facing material choice ☑
  2. Demonstrate that the plasma-facing component can survive under SPARC-relevant cyclic heat loading ⊗

INFUSE collaborators have been flexible to adapt to the evolving needs to apply these aims to an in-progress PFC design activity

  - design activities have led to concepts where low/high cycle fatigue at the component level is no longer a specific concern that requires HHF testing
  - Improved output of program at the plasma facing material choice level

INFUSE Activity Has Adapted to SPARC Needs

- SPARC material down-selection in January 2021 chose tungsten-based materials over carbon-based, identified potential of tungsten heavy alloys
  - INFUSE testing helped to inform damage limits & failure modes which led to inclusion of this alloy in SPARC baseline PFC design
- SPARC value engineering emphasizing ‘design to manufacture’, led to outreach to tungsten suppliers/fabricators
  - upcoming tests to cross-compare surface cutting techniques, speed vs. heat flux handling performance & surface damage

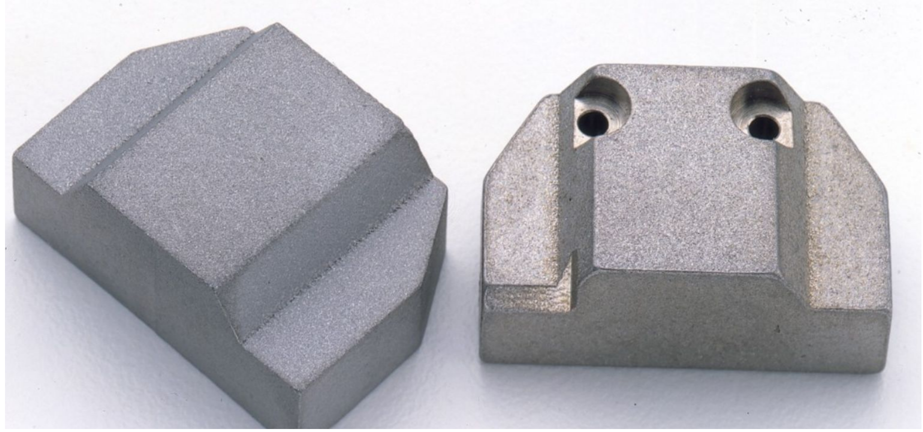
Tasks	2020				2021				2022
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1
Test calibration w/ pure-W									
Pure-W vs. WHA comparisons									
Pure-W fabrication comparisons									

Why is the SPARC PFC Design Using WHA?

- favorable tests in ASDEX Upgrade divertor tiles [Neu JNM 2018]
- WHA thermal properties result in similar rise in temperature for steady-state, pulsed heat flux (up to $T_{limit,WHA}$), despite k(T) being different than pure-W
  - downside is the reduced temperature limit due to the presence of Ni and Fe, limiting bulk temperatures to the melt temperature ~1500 degC
- WHA behaves like a ductile material at all temperatures, not just T_W > DBBT
- WHA has a RT resistivity of ~11 μΩ-cm vs. ~5 μΩ-cm for pure-W which translates directly to eddy current load reduction

WHA has lower risk for 'cold disruptions' when using thick, inertially cooled PFM in high-field devices

- at large QTY, WHA fabricated from near-net-shape pressing + final machining, opening up wider tile shapes at similar cost, duration points

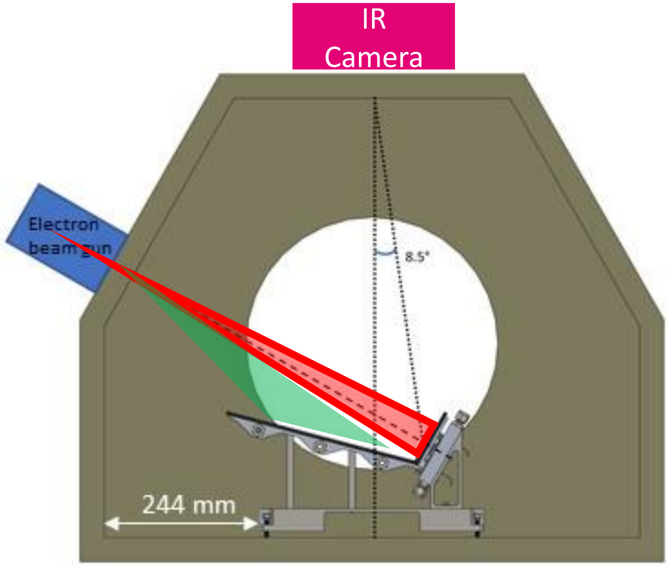


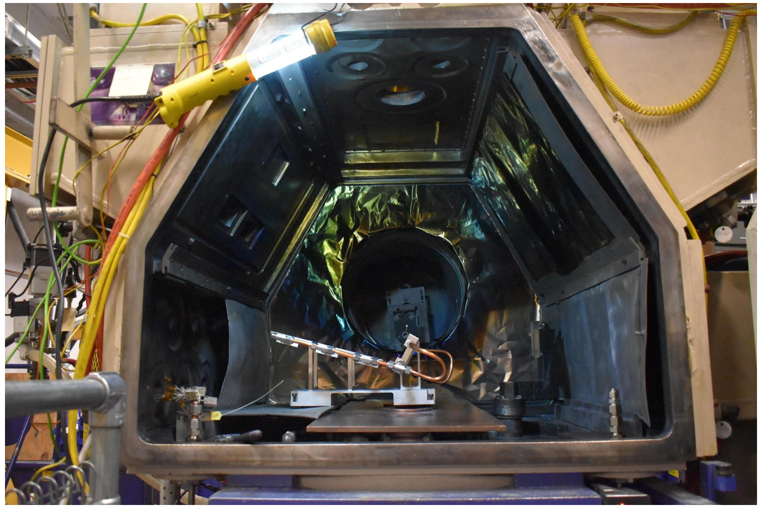
Copywrite HC Starck Solutions

W/WHA Tests to Failure at SPARC Heat Fluxes

SPARC

- ARL Sciaky electron beam:
  - 2 A, 17 kV electron beam
  - Focus down to ~1 mm scale.
  - Target peak heat fluxes: 100-500 MW/m^2
  - Target heat flux factors: 40-100 $MW \cdot s^{0.5}/m^2$
  - PRD high end limit for ELMs, lower limits for disruptions.





OAK RIDGE National Laboratory
PennState Applied Research Laboratory

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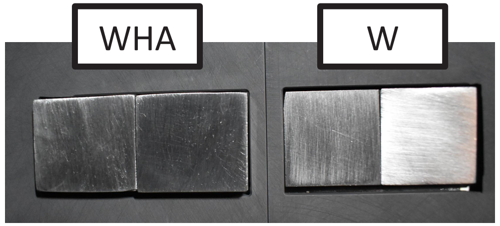

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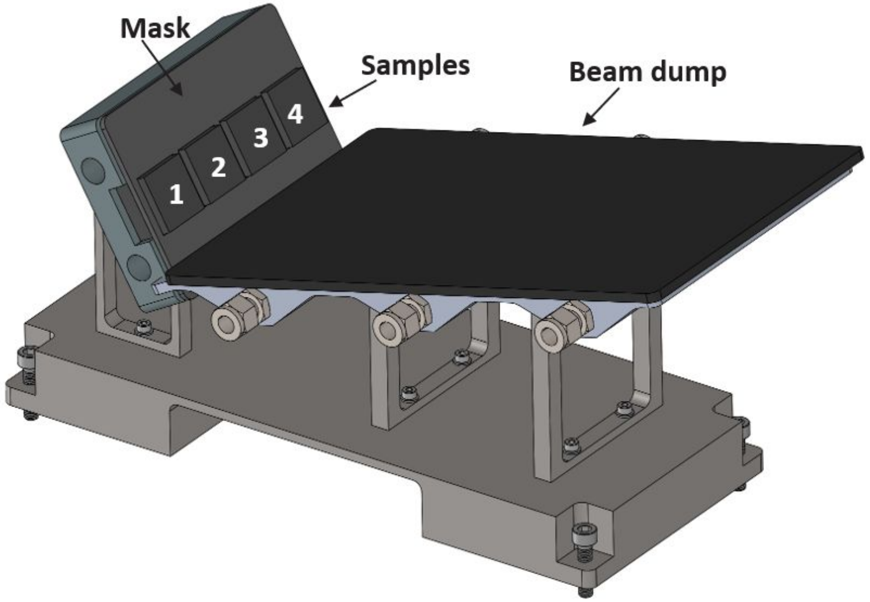
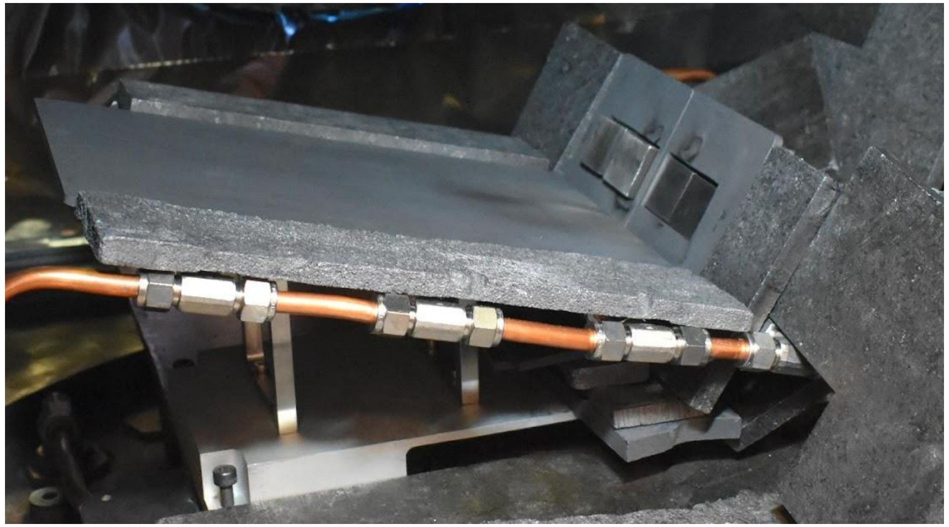
- side-by-side comparison of WHA (Elmet ET97) and pure W tiles (hot rolled)





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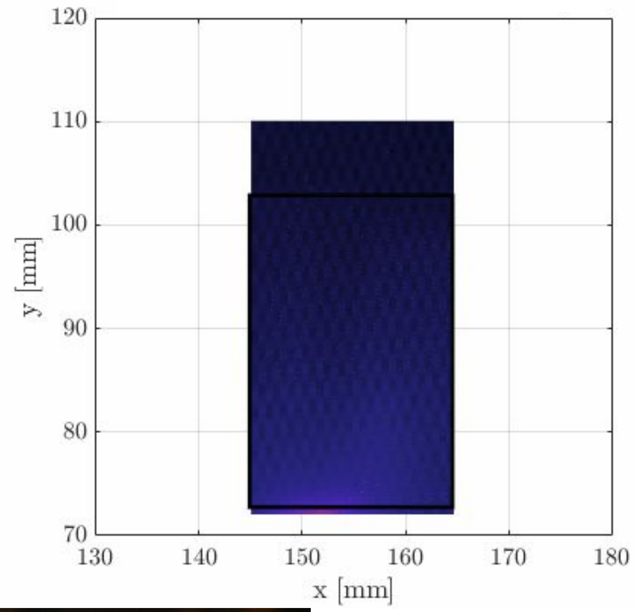
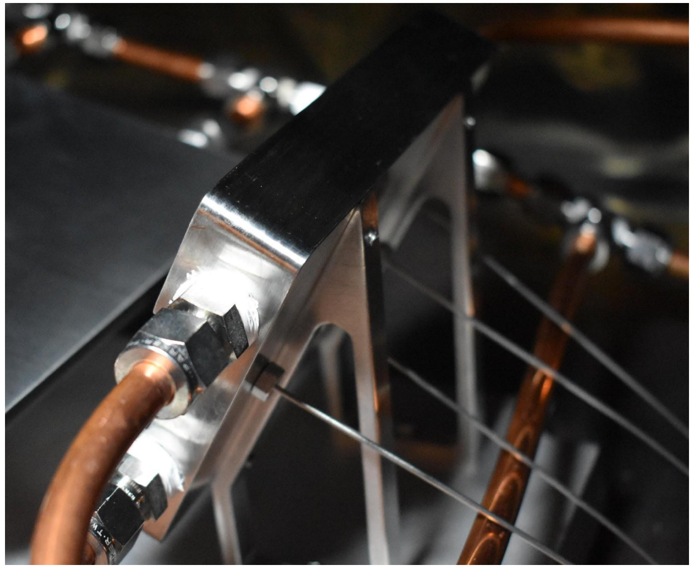
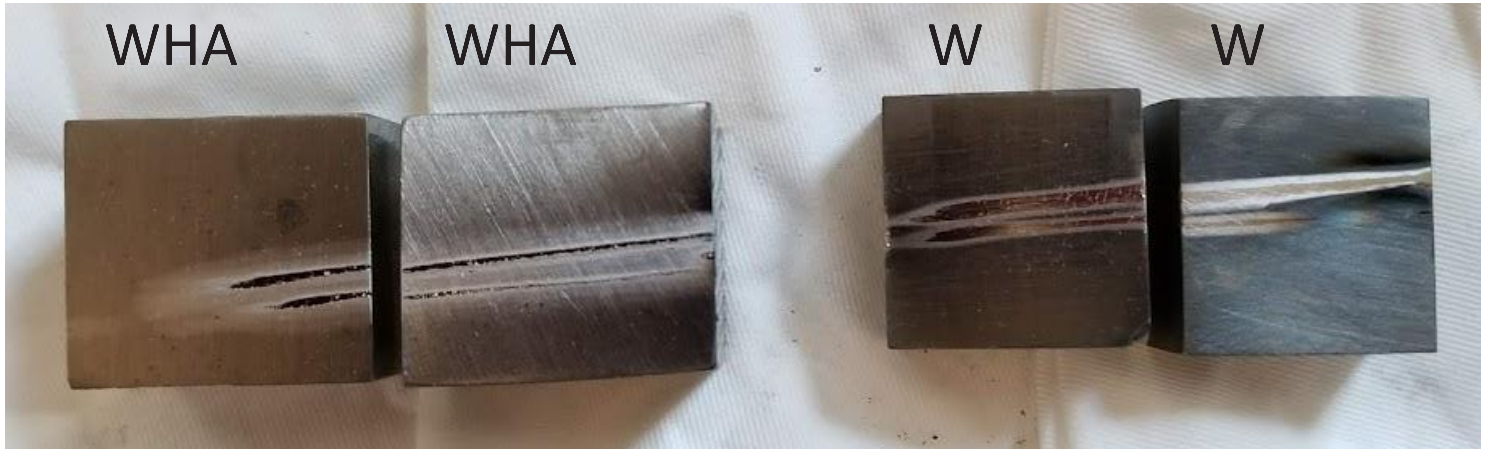
- side-by-side comparison of WHA (Elmet ET97) and pure W tiles (hot rolled)
- diagnostics: IR and visible cameras, rear TC





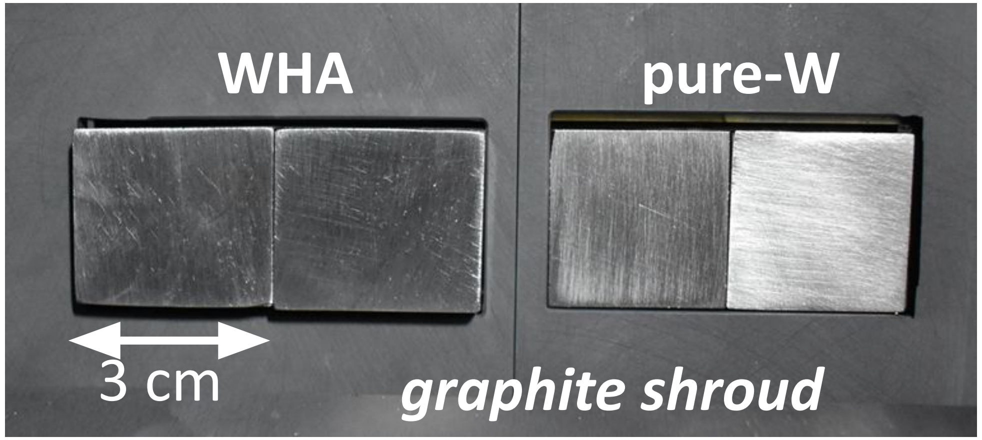
Surface Flash Heating Shows Similar Melt Behavior

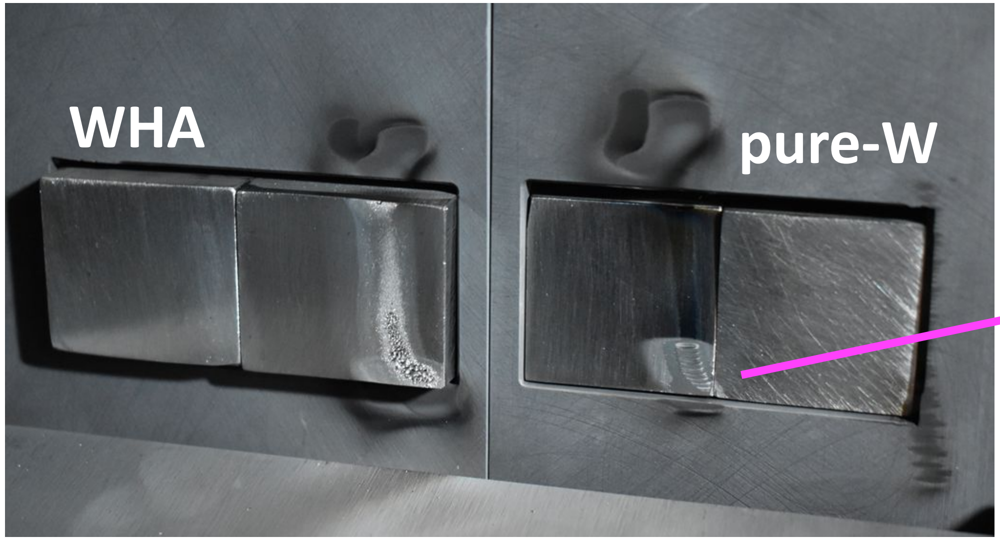
- estimated peak heat flux of ~500 MW/m^2 and a beam velocity of 120 mm/s with a FWHM of ~3 mm using simulation workflow benchmarking energy input via TCs
- suggest that flash melting due to disruptions will not be differentiating.
- consistent with previous work using plasma shock exposures [Laas FED 2020].



Slower Scans Show Differential Failure Mode

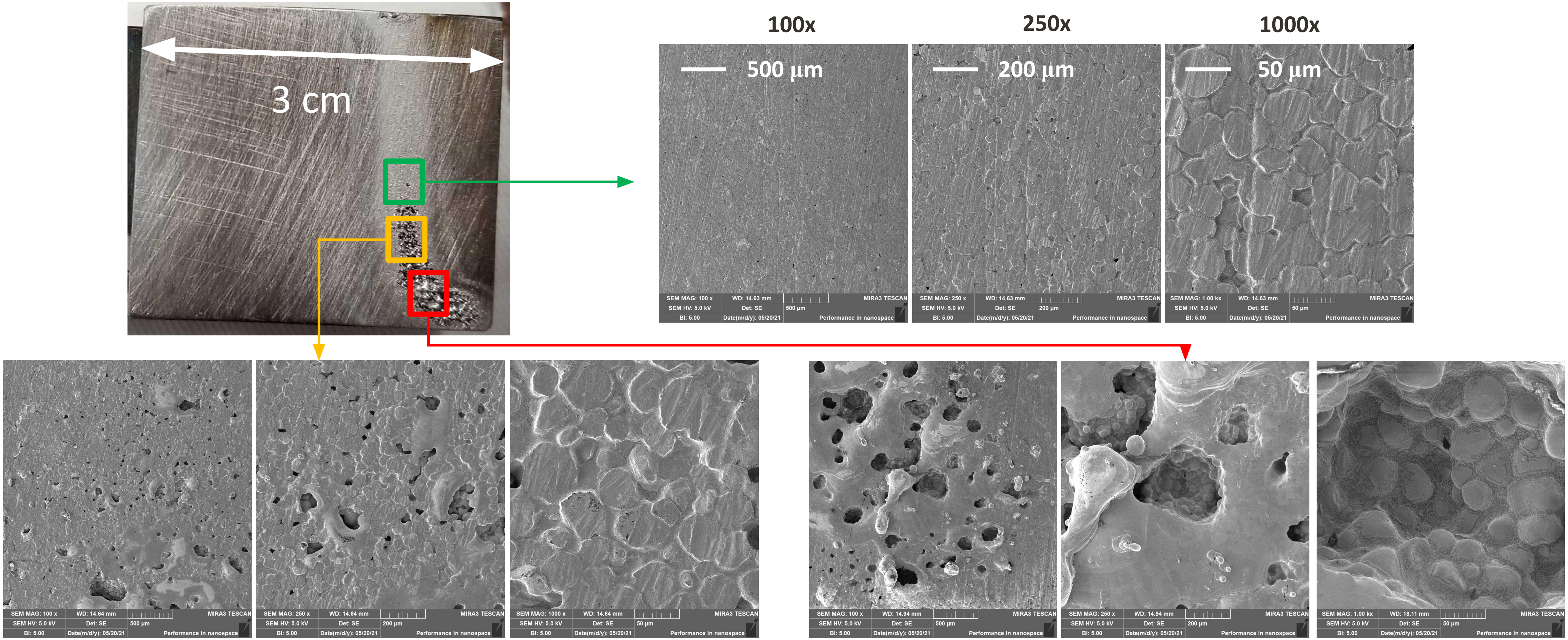
- single(ish) e-beam pass at ~50 mm/s
- estimates show WHA has resilience to ~100+ MW/m^2 transient loads
- WHA fails at >70% of the fluxes that melt pure-W
- WHA failure shows mass loss where pure-W does not





challenges w/ beam control and interpretation support FESAC-LRP recommendation for 'additional high heat flux testing facilities'

SEM Analysis Shows Material Responses



e-beam appears to have passed over the bottom of the sample twice leading to some differential melt/material loss behavior on sample

Summary of Results and Next Steps

- SPARC material selection process in early 2021 identified tungsten but allowed for the possibility of tungsten heavy alloy
  - INFUSE project pivoted in scope to compare pure-W and WHA, but maintained original project aim to inform material selection
- differential behavior, shown at slower speed with mass loss and binder migration observed at heat fluxes >70% of those that would melt pure-W
- this work (+ DiMES testing of WHA on DIII-D) helped inform SPARC's decision for partial use of WHA in lower energy input regions of the PFCs
  - off-midplane limiters (where VDE's go) and inboard limiter (used for start-up)
- next steps:
  - fabricate modifications to test stand to allow comparative testing of pure-W samples
  - obtain tungsten samples from different vendors, with different cutting techniques
  - final e-beam testing to be completed in Q1 2022

Impacts on SPARC

- HHF tests provide useful information to guide material selection of SPARC plasma-facing materials
- CFS has access to a high heat flux exposure facility that allows for straightforward comparison (e.g. 'A to B') tests between material samples to inform internal decision making
- CFS and ORNL can now move on to comparative testing of fabrication approaches that help maintain cost and schedule w/o impacting performance
- aim is to have results to inform PDR, scheduled for March 2022

INFUSE Programs on the SPARC Timeline

SPARC

Divertor Component Testing
Oak Ridge National Laboratory

Divertor Plasma Simulations
Lawrence Livermore National Laboratory

SPARC 3D Field Physics
Lawrence Livermore National Laboratory

Divertor CDR

Materials Downselect

Plasma Facing Components PDR

Error Field Correction Coil PDR

2020	2021	2022	2023	2024	2025

Toroidal Field CDR

Central Solenoid CDR

Limiter CDR

Central Solenoid Model Coil PDR

Central Solenoid PDR

SPARC commissioned

Alpha Particle Diagnostics
PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Superconducting Cable AC Loss and Quench Detection
BROOKHAVEN NATIONAL LABORATORY