Divertor Component Testing
FINAL CRADA REPORT

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1 Technical Overview

1.1 Problem Statement

Power exhaust is an immense challenge in tokamaks. Commonwealth Fusion Systems (CFS), in collaboration with MIT and others, is working on the design of a compact (R_0 = 1.85 m), high-field (B_0 = 12 T) tokamak for the demonstration of net fusion energy, called SPARC. Empirical scaling laws indicate that the unmitigated heat flux in the boundary plasma will exceed 10 GW/m^2. Such high heat fluxes will be a formidable challenge.

The baseline divertor operation scenario for SPARC is to rely on a modest radiation fraction (at least 50%) to get the surface heat flux down to ~100 MW/m^2 and to then sweep the strike point (~0.5 m/s) over the divertor plate. The heat flux is therefore spread over a large area and the surface temperature is kept to a tolerable level. Because SPARC is designed to only run 10-second long pulses, the device does not require intra-shot divertor plate cooling and the associated engineering challenges can be avoided. Such an operational scenario will require very carefully engineered and qualified divertor tiles and cassettes to handle the cyclic thermal loading. Testing of materials under relevant heat flux conditions is a necessary step for developing a robust and reliable power exhaust system, which is the problem tackled under the INFUSE award.

Note that the original problem statement included the testing of components but the scope was reduced to focus on the materials testing. The SPARC project considered the use of tungsten heavy alloys (WHA) as a first wall material and key risks to the project could be retired through the use of high heat flux (HHF) testing on WHA material performance under representative thermal loading.

1.2 Work Scope

The scope of this work is to utilize the HHF testing expertise maintained by ORNL, used in support of NSTX-U and to demonstrate the thermal performance of tungsten-coated graphitic foam targets, to help CFS and its collaborators to assess the performance of (1) base materials (tungsten and its alloys) and (2) divertor mockups under SPARC-like divertor heat flux conditions. These activities will be performed by ORNL personnel using electron beam exposure facilities at the Pennsylvania State University's Applied Research Laboratory (ARL). ARL is a Department of Defense University Affiliated Research Center where ORNL has successfully executed NSTX-U and graphitic foam high heat flux testing using electron beam (e-beam) facilities, which is a non-standard service.

For the assessment of base materials, CFS will do an initial thermal analysis, in consultation with ORNL, to understand under what scenarios the materials are most likely to fail. CFS will supply to ORNL various tungsten-based material samples to test with testing taking 3 weeks. ORNL will thermally stress the samples under SPARC divertor-like conditions to either failure or to a prescribed number of pulses. ORNL will record experimental data, including IR surface temperature and embedded thermocouple readings, and report results to CFS.

Tasks included:

1. Base Material Calibration
2. Base Material Assessment
3. Completion of Final Report

1.3 Results

The results from this proposal can be broadly categorized into the two rounds of testing that were carried out at ARL with support from ORNL personnel and members of the SPARC design team. A third round of testing was planned but due to the supply chain issues, the samples did not arrive prior to the close out deadline of the CRADA. Nonetheless some of the lessons learned from preparing for the third round of testing are discussed here.

The first round of testing was executed over two weeks from the 21st of September to the 2nd of October 2020. The primary purpose of this first round of testing was to assess if the Sciaky electron beam facility at ARL could achieve the desired heat fluxes and the beam control was sufficient to replicate SPARC divertor target heat fluxes. If target conditions could be met, then tungsten tiles were to be tested until failure. This first round of testing aimed to complete Task 1 and part of Task 2. The target conditions were:

- Surface heat flux level of between 100-500 MW/m^2;
- Swept at velocities of ~0.5 m/s
- cycled past the samples 20 times in a 10 sec period

These conditions aimed to mimic the worst-case thermal loads anticipated for the strike point sweep on SPARC [Kuang2020]. Significant beam development time was planned since previous testing for the graphite NSTX-U tiles was limited to exposing the PFC assembly to a quasi-stationary heat flux for durations relevant for NSTX-U [Gray2021]. The candidate base material used in the CFS tests was tungsten and the goals were to calibrate the IR camera, absorbed heat flux, beam control pattern, and perform a fatigue test. An actively cooled test stand (Figure 1) was developed to hold the samples, with tungsten material in this initial test taken from left-over tiles from Alcator C-Mod [Lipschultz2012]. The test stand was designed by the SPARC team with input from ORNL. Key features include: a graphite beam dump for beam start up and to park the beam between sweeps; and a graphite mask to protect the sample holder from exposure to the beam. The mask is thermally isolated from the samples and supported from the beam dump. Much of the initial design work went towards the beam dump. Due to the increased absorption coefficient of carbon relative to tungsten and the fourfold increase in the duration the e-beam spent on the dump relative to the samples, it was important the beam dump did not overheat during the experiment.

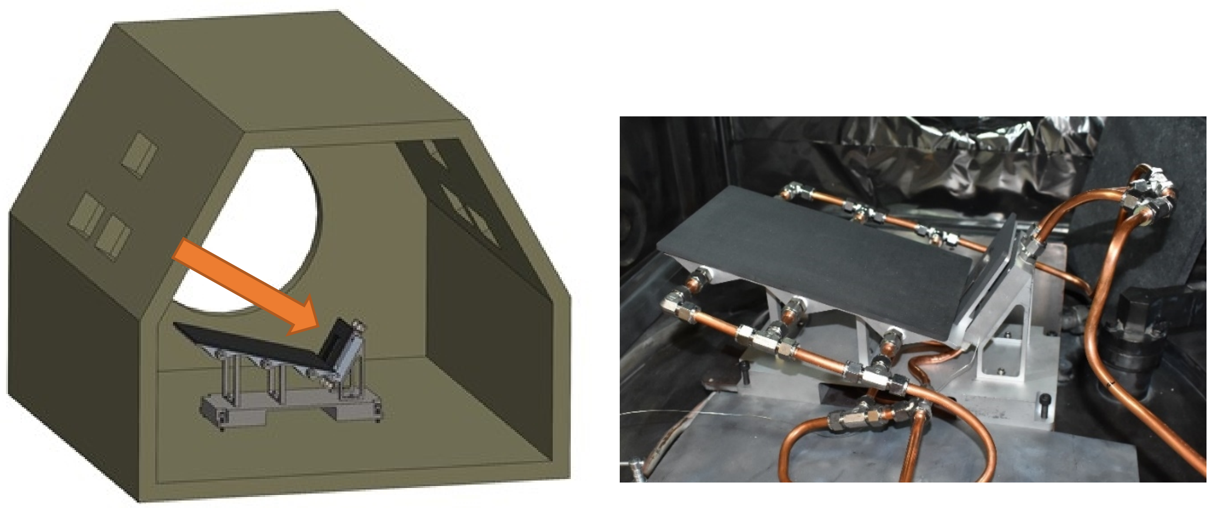
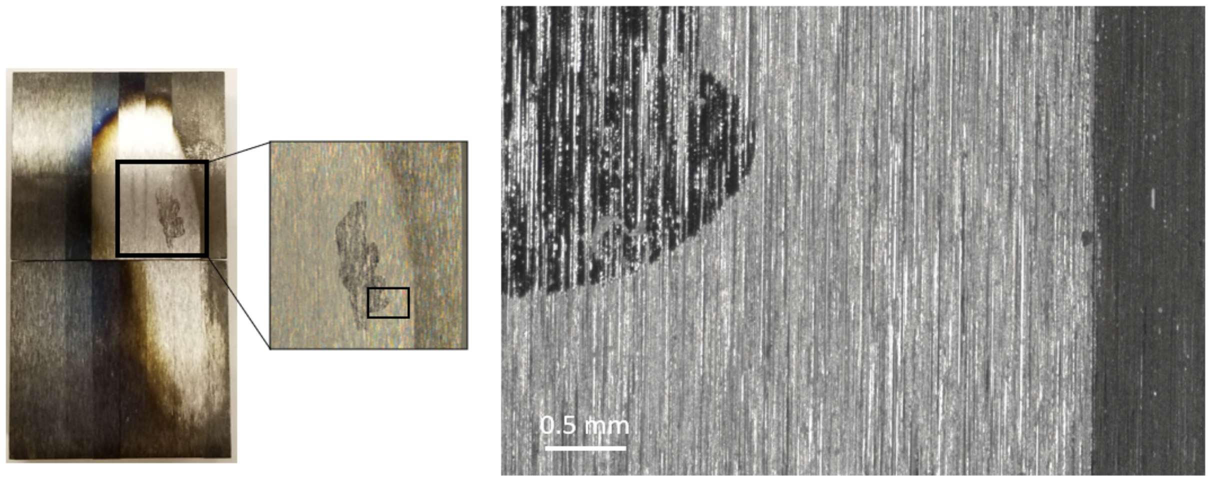


Figure 1: (Left) CAD rendition of the e-beam chamber with the test stand. The samples are held normal to the beam to maximum surface heat flux while the beam dump is inclined to have a grazing incident heat flux. (Right) Picture of the test stand in the chamber with active cooling manifold.

Following sample exposures, it was concluded that the e-beam facility could reach the >100 MW/m^2 target heat fluxes and a tungsten absorption coefficient of 0.2-0.25 of the incident e-beam power was estimated. Following low level cyclic testing, some surface melting of the tungsten samples was observed but no major crack networks were formed (Figure 2). Broadly speaking the test results supported the thermal analysis performed that inertially cooled tungsten tiles would likely survive the divertor target heat fluxes anticipated for a single SPARC primary reference discharge. High cycle testing was not performed due to cooling issues with the test stand and thus information on the lifetime fatigue performance was not collected.



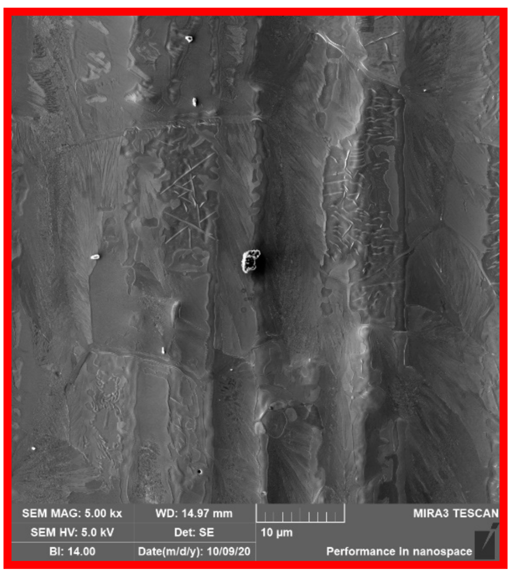


Figure 2: Tungsten samples exposed in the first round of testing. Surface melting of the tungsten is observed following a 10 sec test cycle. The melt layer is extremely shallow and one can still surface the scratch marks from the grinding surface finish. Some micro-cracking observed under SEM images at the 10 µm scale but no macro-cracking.

A second round of high heat flux testing was carried out from 17th to 21st May 2021. At this point in the SPARC design process, the decision to use tungsten-based material for the first wall had been made. However, an open decision existed on whether pure tungsten or tungsten heavy alloy (WHA) was to be used. WHA is a sintered material that comes in a variety of chemical compositions. CFS was interested in a variation comprised of 97% Tungsten, 2% Nickel, and 1% Iron where grains of the tungsten phase are suspended in a matrix of the Ni-Fe phase. This material has been explored extensively for use in ASDEX-U and was installed for one campaign [Neu2018]. Compared to tiles made with pure-W, WHA-based tiles are cheaper to machine and ductile at room temperature, reducing the risk of mechanical failures due to disruption electromagnetic forces early in the discharge when pure-W will still be below the brittle to ductile transition temperature. However, the presence of iron and nickel, which significantly lowers the melting temperature of WHA compared to pure tungsten, meant that a mechanism existed for WHA to have more expansive damage compared to pure-W, when exposed to similar transient heat loads. Tests performed by the ASDEX-U team exposed the WHA with thermal loads of up to 20 MW/m^2 for 3 seconds and surface temperatures up to ~2200 °C [Neu2017]. Although the temperatures were likely representative of anticipated surface temperatures in the SPARC divertor, it was unclear how the WHA would behave if exposed to short transient bursts of high heat fluxes which is a closer representation of SPARC risks including the swept strike point on the divertor target plates, small ELMs or the thermal quench of mitigated disruptions. Therefore, during the second round of testing, identifying the risks associated with using WHA as a first wall material in SPARC was prioritized.

Two tests were carried out, using newly procured pure-W and WHA material samples. The first involved a focused e-beam with peak surface heat fluxes of >500 MW/m^2 swept quickly to keep the exposure time to ~50 ms. The thermal load was meant to mimic exposure to a large edge localized mode (ELM) or small disruption. Under these loads, the WHA performed similarly to the pure tungsten. Both materials went straight to melt (Figure 3) and the surface morphology looked similar under a light microscope. The results were promising for the use of WHA since the material response to the thermal load was not discriminating, e.g. the advantages of WHA could be obtained with similar downside risks.

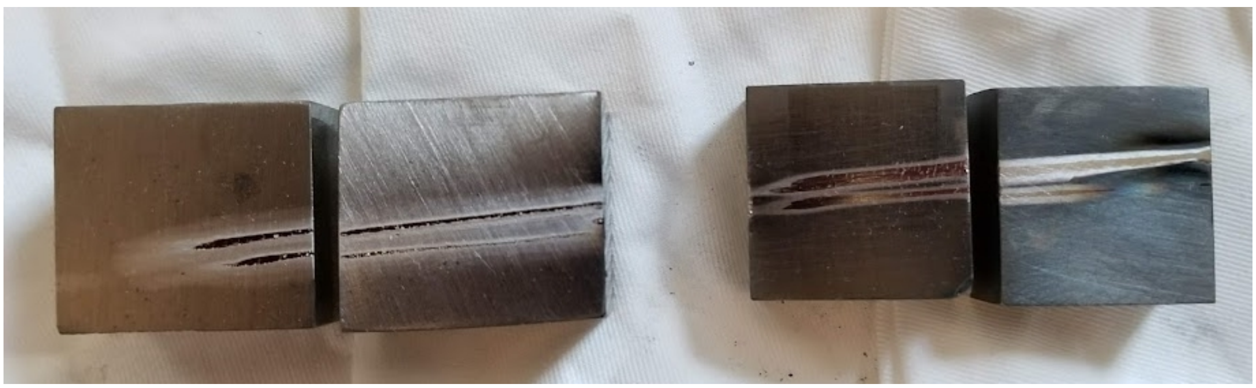


Figure 3: Left 2 tiles are WHA and right two tiles are pure tungsten. When exposed to heat fluxes >500 MW/m^2 for ~50 ms. Both materials demonstrated that they would go straight to surface melting. The beam path can clearly be seen across the four tiles.

The second test was to expose the samples to ~100 MW/m^2 heat fluxes with exposure times in the ~100 ms range, similar to if the strike point sweep frequency was unintentionally reduced. The beam was swept over the tiles two consecutive times. Figure 4 shows the samples prior to (top) and after (bottom) exposure. The path of the e-beam can clearly be traced from the damaged surfaces of the samples. A first pass was made across the full length of the samples while a second partial excursion up the bottom right corner of the samples can be seen. Over the course of two sweeps, the surface temperature was raised high enough to result in tungsten surface melt. However, the WHA tile 'failed' in the first pass and resulted in significant surface roughening and the ejection of material. One can see in Figure 5 large perforations in the WHA surface. Within the cavities, the tungsten beads of the sintered material can be seen. EDS measurements in this perforated region indicate there is only pure tungsten and there is no nickel or iron present. Figure 6 shows images during the test comparing the WHA (left) to pure tungsten (right). An ejection of material from the WHA surface can clearly be observed, while pure-W exhibited an as-expected formation of melt layer which solidified without large-scale mass loss. While these tests don't fully capture the relative risk as melt layers in tokamaks exhibit a JxB force, it was assumed that the material loss phenomenon of WHA would be reproduced if a similar exposure occurred on SPARC.

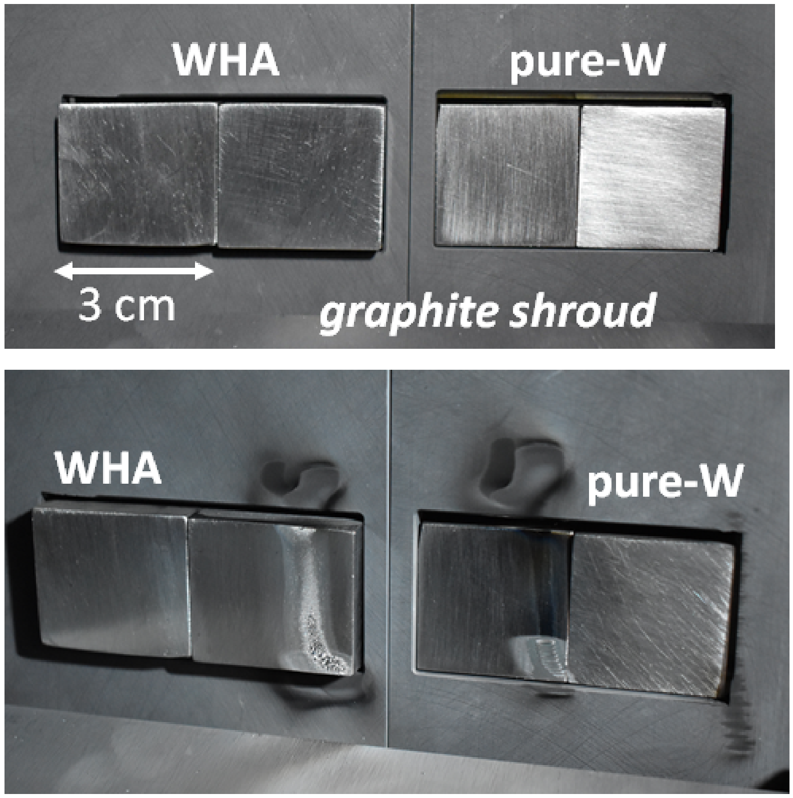


Figure 4: Images of samples prior to (top) and after (bottom) exposure to the Sciaky e-beam. The beam path can clearly be seen on the WHA samples traversing the full length of the sample and then a second pass up ~1/5 of the bottom right corner of the samples.

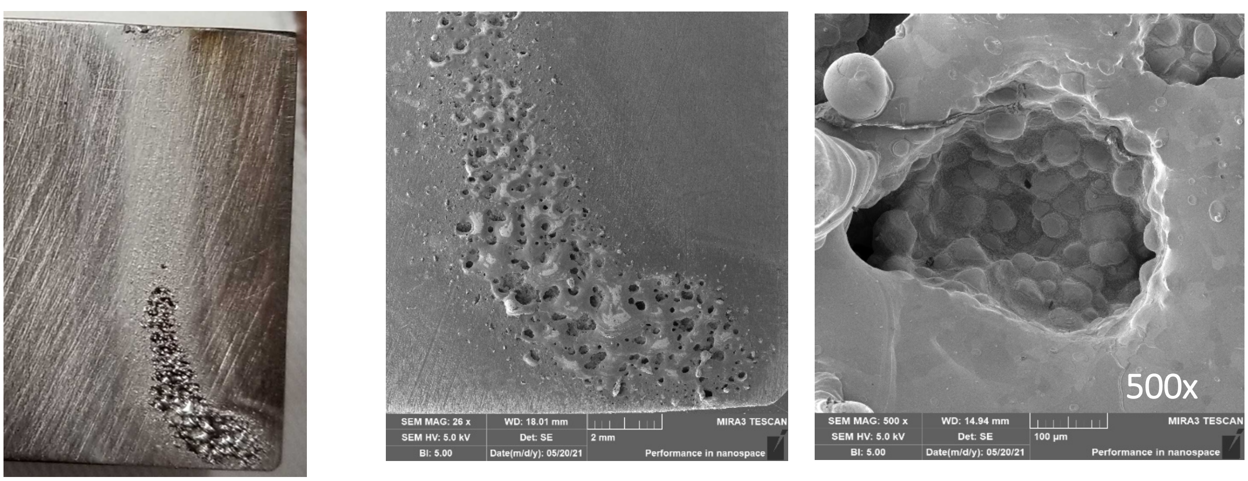


Figure 5: Perforation of the WHA surface following exposure to ~100 MW/m^2 with exposure times of ~100 ms. SEM images middle and right to smaller scales. The surface was entirely tungsten with no nickel and iron present. The individual tungsten beads from the sintering process can be seen in the cavities.

Figure 6: Visible light images from the e-beam hitting the sample surface. Left: Sparks flying off the WHA is an indication of the surface material being ejected during the exposure. Right: Whereas in contrast, when the e-beam hits the pure tungsten surface only the lens flaring from the bright exposure is observed.

The observations from these tests raised significant concern for the use of WHA in SPARC in areas where there would be a risk of heat flux control. An enhanced failure mode, relative to pure tungsten, has been observed in WHA at transient thermal loads (~$MJ/m^2s^{0.5}$) close to, but less than, that which can cause pure tungsten to melt. As a result of these test results, the use of WHA has been restricted to regions of the device where quasi-steady thermal loading is anticipated to be reduced. The divertor high heat flux target plates and the outer limiter plasma facing material will continue to be pure tungsten, while the inner cylinder and off-midplane limiters are being developed using WHA. While these later surfaces will be exposed to transient heat fluxes from unmitigated vertical displacement event disruptions, transient thermal loads are above that which will melt pure-W and feature the highest electromagnetic loads, and so the favorable engineering properties of WHA discussed above motivate their use on a mission-driven device like SPARC.

As mentioned, a third and final round of testing was initially planned for this proposal. To ensure that SPARC is on schedule, the material order for all the raw tungsten plates will be placed before final design is completed. To assist with the supplier selection, tungsten samples from different suppliers with different surface finishes, including different tungsten cutting techniques, are to be exposed to high transient thermal loads to determine if there is any discriminating behavior. Similar testing had been done to qualify the ITER tungsten mono-block vendors. It was determined that the supplier material testing was to be done instead of the divertor mock up as the results of the heat flux testing would have a clear impact on the design and manufacturing of SPARC. However, due to supply chain delays, the tungsten samples did not arrive in time to be tested prior to the closing date of this proposal. Although the third test could not be executed, the experience gained by the SPARC design team through the collaboration with ORNL personnel have given the team the confidence to begin setting up a direct contract with ARL so as to finish this last phase of the base material assessment.

2 Impact

2.1 Use of Project Results

The results from these the high heat flux testing carried out as part of this proposal has been beneficial towards the selection of the SPARC plasma facing material. There was significant concern on the use of tungsten and how robust it would be when exposed to the anticipated heat loads on SPARC. The first round of testing clearly supported the thermal simulations that suggested melting of the tungsten tiles could be avoided with the use of the strike point sweep. Alongside other investigations, the test results contributed to the final decision to go with a tungsten first wall device instead of carbon.

The second round of testing provided clear evidence of differentiating behavior between pure tungsten and WHA when exposed to large transient thermal loads. The ejection of material from the surface of the WHA and the clear pooling of melted material on the WHA surface raised concerns on the use of WHA in the high-heat flux regions of SPARC and was the determining factor in restricting its use to regions of the devices where lower thermal loading is anticipated. Despite the increased difficulty of designing tile components using pure tungsten, the high heat flux target plates in the divertor and the outer limiter would still be made from pure tungsten.

Lastly, the knowledge transfer from ORNL personnel to the SPARC design team on how to design and execute a series of high heat flux testing was invaluable. Further materials and component qualifications for SPARC need to be carried out but the team in confident in its abilities. Looking beyond SPARC, material qualification for ARC will require similar high heat flux testing activities. The experience gained by working alongside the ORNL personnel will be important to ensuring that clear decision quality data can be gathered from these testing activities.

2.2 Fusion Energy Impact

Through the extended qualification of the use of WHA in SPARC, the results from these tests join a growing body of knowledge on the viability of this material in a fusion environment. At present W7-X is also exploring the use of WHA though of a different composition. WHA is attractive due to its ductility and reduced manufacturing cost, but the impact of its unique temperature limits must be understood for robust plasma operation. It will be a useful material to consider in the design of early fusion power plants, although faces constraints on its use due to the presence of nickel and iron which can lead to activation concerns.

The high heat flux capability at ARL has been critical to unlocking the behavior of W and WHA materials in SPARC-like thermal conditions. However, as an electron beam, it does have limitations such as small spot size and unwanted electron/material interaction. The usefulness of the results presented here to the design of plasma facing components for SPARC, as well as challenges faced in achieving these results, highlights the necessity of investing in additional high heat flux sources in the United States.

2.3 Intellectual Property, Publications and Conferences

The results from this project were summarized into the following conference presentation and publications are in-progress:

- Kuang, A.Q., et al. "Investigations of tungsten heavy alloy (WHA) for use on SPARC." Contributed Poster at the 63rd Annual Meeting of the APS Division of Plasma Physics, 2021.
- Reinke, M.L., et al "SPARC Divertor Mission, Physics and Engineering Basis" Contributed Poster at the 63rd Annual Meeting of the APS Division of Plasma Physics, 2021
- Gray, T.K., et al. "High Heat Flux Exposures of Tungsten and Tungsten Heavy Alloy Materials for Plasma Facing Components for SPARC." Contributed Oral at the 29th IEEE Symposium on Fusion Engineering, 2021.

3 References

[Kuang2020] Kuang, A. Q., et al. "Divertor heat flux challenge and mitigation in SPARC." Journal of Plasma Physics 86.5 (2020).
[Gray2021] Gray, T. K., et al. "High Heat Flux Testing of Castellated Graphite Plasma-Facing Components." Fusion Science and Technology 77.1 (2021): 9-18.
[Lipschultz2012] Lipschultz, B., et al. "Divertor tungsten tile melting and its effect on core plasma performance." Nuclear Fusion 52.12 (2012): 123002.
[Neu2017] Neu, R., et al. "Investigations on tungsten heavy alloys for use as plasma facing material." Fusion Engineering and Design 124 (2017): 450-454.
[Neu2018] Neu, R., et al. "Results on the use of tungsten heavy alloys in the divertor of ASDEX Upgrade." Journal of Nuclear Materials 511 (2018): 567-573.