Final Technical Report for DoE award DE-SC0021338
"Hypervelocity impact in stellar media: heat shielding, shock fronts and ablation clouds"

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The Frontier Plasma Science experiments carried out and analyzed by our team under this award modeled the processes occurring during spacecraft atmospheric entries and meteorite planetary collisions by inserting material targets into the Scrape off Layer (SOL) and edge plasma of the DIII-D tokamak. This project investigated important plasma-material processes during high-enthalpy atmospheric entries, including heat flux generation and material ablation. Exploration missions to the Solar System's gaseous giants and hyperbolic re-entries into the Earth's atmosphere require spacecraft that can withstand high velocity (>10 km/s), high heat fluxes (>10 MW/m^2), and corresponding enthalpies. Ablative materials have been used as thermal shields to protect the spacecraft from severe heating during entry. However, developing high enthalpy ablating materials is challenging due to the lack of adequate ground testing facilities. Our team stated that the performance of candidate shielding materials could be assessed in a laboratory environment with multiple in-situ diagnostics, which was enabled by the progress in the tokamak research. Modern machines feature relatively long discharges (~10 s) with well-controlled stable plasma conditions at the edge where the heat flux and the flow speed are similar to those experienced during atmospheric entries.

The experiments were carried out at the DIII-D National Fusion Facility in San Diego, CA, operated by General Atomics (GA) for the DoE. The experimental proposal was submitted to the DIII-D program committee and, upon careful consideration and review by an external scientific committee, was granted experimental time on DIII-D in the FY2020-21 experimental campaign. DIII-D offers an ideal environment for this project due to the inherent properties of the tokamak plasma – rotation of the core and edge plasma and fast flow in the SOL (parallel to the B-field). Any object launched radially from the wall with zero toroidal speed incurs motion relative to the plasma in excess of ~50 km/s, which, for example, is comparable to the entry velocity of 47 km/s for the Galileo probe to Jupiter. This approach allows studying plasma-material interactions in the projectile frame of reference, avoiding the need to build a hypervelocity projectile launcher. Therefore, all the diagnostics can be localized near the injection point and focus on the projectile while it still exhibits only minimal speeds in the laboratory frame. The high plasma temperatures in the tokamak plasma are comparable to the temperatures expected for gas giant spacecraft entries. Such temperatures of $\lesssim$100 eV were unattainable even in NASA's Giant Planet Facility, utilized for heat shield testing for the Galileo probe mission.

DIII-D has one of the strongest research programs in the area of Plasma-Material Interactions (PMI), thanks to the versatile suite of diagnostic tools. Most of them were useful for the experiments without modification. The core of the PMI diagnostics is the Divertor Materials Evaluation System (DiMES), which can be configured to expose objects smaller than ~5 cm. Probe sizes ranging from a few 100 μm to the DIII-D pellet size (a few mm to 1 cm) were adjusted to ensure the safe exposure of heat shield material (avoiding plasma disruption). The DIII-D core and edge plasma conditions (density and temperature) were varied in a heated L-mode discharge to provide stable plasma and allow for scans over a range of entry-relevant conditions experienced by the probe material. Scaling techniques were developed to extrapolate these results to larger projectiles, longer exposures, and a wider parameter space. This allowed for comparison with experimental data from previous space flight missions and other on-ground testing facilities. Thus, the above represented a unique experiment of great interest to the aerospace engineering, planetary science, and plasma physics communities.

During the two years of this award, the UC San Diego and Baylor/Auburn teams made the following progress on the research tasks within this project:

1. DIII-D DiMES launcher:

   The DIII-D DiMES launcher was designed and manufactured in preparation for the DIII-D Frontiers campaign experiments. The designed launcher uses the standard DIII-D DiMES head and can be inserted into or extracted from the vessel during the standard DIII-D between-shot pit runs. The launcher uses four independently controlled pistons and can propel pellets into the DIII-D vessel at a speed of up to 10m/s. The launcher was successfully used on this experiment in April of 2021 and on several other experiments led by the UC San Diego researchers. The success of UC San Diego's DiMES launcher design led to the fabrication of several more DiMES launcher heads, and several DIII-D Plasma Material Interaction focused experiments took advantage of the system to study the transport and ablation of slow pellets of different materials and sizes launched from the DIII-D wall into the scrape-off layer and core of the plasma.

2. DIII-D DiMES carbon ablation rod system.

   The DIII-D DiMES head system was successfully adapted to expose up to three carbon rods of different cross-sections protruding approximately 1.5-2 cm above the vessel floor tiles. The system was successfully used in the DIII-D Frontier campaign experiments in April of 2021, and visible ablation was observed after exposure to high heat fluxes in the DIII-D L-mode discharges.

3. Frontier Science campaign experiments on DIII-D.

   Two half-days of experiments have been successfully carried out on the DIII-D tokamak by a collaborative team of the UC San Diego, Baylor/Auburn, and Stuttgart Universities, and General Atomics. The results for complete carbon pellet ablation and partial carbon rod ablation were obtained.

4. SiC coating ablation.

   A number of the carbon ablation rods were coated with the 30-micron SiC layer during the manufacturing of the carbon ablation rods. SiC-coated rods were successfully exposed to high heat fluxes in the DIII-D experiments, and the data on the SiC coating ablation was obtained.

5. Carbon ablation models.

   Several different carbon ablation models have been analyzed in relation to the DIII-D experiments. Predictive simulations were performed before the experiments to estimate the expected mass loss. Post-experimental calculations are done to verify the prediction of the models.

6. UEDGE-DUSTT simulations.

   Predictive UEDGE-DUSTT simulations have been performed by UC San Diego researchers for carbon pellets of different sizes launched into the DIII-D L-mode discharges at different vertical velocities. The results of these simulations guided the team during the planning stage of the DIII-D experiments.

   Post-experimental modeling in UEDGE-DUSTT was performed to analyze the dynamics of the pellets, assist in the analysis of the experimental results, and verify the physics in the DUSTT code. The experiments performed under this award allowed verification of DUSTT models against the DIII-D data and in developing new models in the code for transport of large pellets and ablation of carbon of large pellets.

7. IPG-6 dust experiments.

   A set of accompanying experiments on understanding dust transport in different plasma conditions was carried out on the IPG-6 device at Baylor University by G. Griffin, T. Hyde, D. Orlov, and E. Kostadinova. The results of this experiment were presented by G. Griffin at the annual APS DPP meeting in November of 2021.

The award period coincided with the COVID-19 pandemic, and as the research team members were located at different universities in the US and abroad, the collaboration was organized via regular meetings on Zoom at least twice a month to discuss the planning of the experiments and to analyze the experimental results. The Baylor/Auburn University team, consisting of PI E. Kostadinova, one undergraduate student, Davis Carter, and one graduate student, Graeson Griffin, traveled to San Diego to participate in the DIII-D experiments in April of 2021.

The award allowed D. Orlov to participate as a mentor in the UC San Diego Mechanical and Aerospace Engineering Senior Design project. In collaboration with the course instructor, M. Ghazinejad D. Orlov mentored five UC San Diego MAE undergraduate students (M. Hanson, J. Escalera, H. Taheri, C.N. Villareal, D.M. Zubovic). The students were involved in the design of the carbon rods for the DiMES carbon rod ablation system. During this educational process, the student team worked closely with members of the DIII-D team to understand the requirements and limitations, as well as the process of design review at the DIII-D National Fusion Facility.

The design of the DiMES carbon ablation rod system, as well as the experimental results, were published in the ASME IMECE 2021 Proceedings (full citation provided below). All five UC San Diego involved in the project were co-authors of the publication. For several of them, this was the first scientific publication in their careers.

The following publications and presentations are associated with this award:

DM Orlov, MO Hanson, J Escalera, H Taheri, CN Villareal, DM Zubovic, I. Bykov, E.G. Kostadinova, D.L. Rudakov, M. Ghazinejad, “Design and Testing of Dimes Carbon Ablation Rods in the DIII-D Tokamak”, arXiv, arXiv:2106.08306 (2021)

ME Fenstermacher, DM Orlov, et al., "DIII-D research advancing the physics basis for optimizing the tokamak approach to fusion energy ", Nuclear Fusion, Volume 62, 042024, 2022. https://doi.org/10.1088/1741-4326/ac2ff2

D.M. Orlov, MO Hanson, J Escalera, H Taheri, CN Villareal, DM Zubovic, I. Bykov, E.G. Kostadinova, D.L. Rudakov, M. Ghazinejad, “Design and Testing of Dimes Carbon Ablation Rods in the DIII-D Tokamak”, ASME 2021 International Mechanical Engineering Congress and Exposition Proceedings, Volume 4: Advances in Aerospace Technology, Paper No: IMECE2021-73326, V004T04A038 (2021) https://doi.org/10.1115/IMECE2021-73326 (2022)

EG Kostadinova, DM Orlov, I Bykov, J Schmidt, G Herdrich, LS Matthews, TW Hyde, “Small Grains, Hyper Impact: Frontier Science at the DIII-D Tokamak”, 62nd Annual Meeting of the APS Division of Plasma Physics, online, Nov 9-13, 2020

EG Kostadinova, DM Orlov, G Griffin, J Schmidt, TW Hyde “Dust clustering in Inductively Heated Plasma Jet”, American Physical Society Gaseous Electronics Conference, Huntsville, AL, October 5, 2021

G Griffin, E Kostadinova, DM Orlov, J Schmidt, D Crater, R Smirnov, I Bykov, D Rudakov, K Ulibarri, TW Hyde, “Observing Dust Response in an IPG Plasma Jet”, 63rd Annual Meeting of the APS Division of Plasma Physics, Pittsburgh, PA, Nov 8-12, 2021

EG Kostadinova, DM Orlov, C Mehta, “Carbon Ablation in Extreme Heating Environments”, 63rd Annual Meeting of the APS Division of Plasma Physics, Pittsburgh, PA, Nov 8-12, 2021

DM Orlov “Hypervelocity impact in Stellar Media: Spacecraft Heat Shield Study in DIII-D”, 63rd Annual Meeting of the APS Division of Plasma Physics, Pittsburgh, PA, Nov 8-12, 2021 (invited)

R Smirnov, I Bykov, J Guterl, EG Kostadinova, DM Orlov, DL Rudakov, “Modelling Carbon Pellet Injection in DIII-D Divertor for Advanced Material Studies”, 63rd Annual Meeting of the APS Division of Plasma Physics, Pittsburgh, PA, Nov 8-12, 2021

DM Orlov, EG Kostadinova, I Bykov, DL Rudakov, R Smirnov, “Impurity Transport Studies Using DiMES Pellet Launcher in DIII-D”, US Transport Task Force meeting, Santa Rosa, CA, April 5-8, 2022

I. Bykov, D.L. Rudakov, E. Kostadinova, C. Lasnier, W. Meyer, C. Marini, A. McLean, D.M. Orlov, R.D. Smirnov, “Compact Injector For Studies Of Solids Interaction With Fusion Plasmas”, High Temperature Plasma Diagnostics conference, 2022

Rudakov DL, Orlov DM, Kostadinova EG, Bykov I, Escalera J, Guterl JG, Hanson MO, Lasnier CJ, McLean AG, Perillo R, Smirnov R, “Studies of graphite ablation in DIII-D divertor”, Plasma Surface Interaction PSI-25 meeting, Jeju, Korea, June 13-17, 2022

I. Bykov, R. Smirnov, D.M. Orlov, E.G. Kostadinova, C. Lasnier, W. Meyer, D.L. Rudakov, C. Marini, J. Guterl, “Granule transport through the divertor scrape-off layer studied by injection from DiMES in DIII-D”, Plasma Surface Interaction PSI-25 meeting, Jeju, Korea, June 13-17, 2022

DM Orlov, EG Kostadinova, I Bykov, DL Rudakov, R Smirnov, J Guterl, J. Schmidt, MO Hanson, A. McLean, C. Marini, C. Lasnier, F. Scotti, C. Chrystal, B. Wilcox, H. Wang, J. Herfindal, L. Carlsson, T. Wilks, A. Hyatt, J. Barr, A. Bortolon, S. Bringuier, G. Griffin, D. Crater, J. Escalera, D. Zubovic, H. Taheri, C. Villareal, T. Hyde, L. Matthews, G. Herdrich, C. Mehta, C. Marini, R. Perillo, M. van Zeeland and the DIII-D team, “Spacecraft heat shield study in DIII-D”, MagNetUS 2022, Williamsburg, VA, June 7, 2022

Mehta C.A., Kostadinova E.G., Orlov D.M., Formation of organic compounds through meteoritic atmospheric shock”, 2^{nd} MagNetUS organization annual meeting, Williamsburg, VA, June 7, 2022

I. Bykov, R. Smirnov, D.L. Rudakov, D.M. Orlov, E. Kostadinova, C. Lasnier, W. Meyer, A. McLean, C. Marini, M Van Zeeland, J. Guterl, “Studies of UFO Transport and UFO-triggered disruptions with UFO launcher embedded into DiMES material probe in DIII-D”, 11^{th} ITER International School, San Diego, CA, July 2022

CA Mehta, EG Kostadinova, DM Orlov, “Ablation of Carbon Objects within Jovian Atmosphere”, 64th Annual Meeting of the APS Division of Plasma Physics, Spokane, WA, Oct 17-21, 2022

CA Mehta, EG Kostadinova, DM Orlov, “Ablation of Carbon Objects within the Jovian Atmosphere”, American Physical Society's Division of Plasma Physics 64th annual meeting, Spokane, WA, October 17-21, 2022

DM Orlov, EG Kostadinova, I Bykov, R Smirnov, DL Rudakov, MO Hanson, CA Mehta, C Marini, R Perillo, and the DIII-D team, ", Spacecraft heat shield study in DIII-D", APS March Meeting, Las Vegas, NV, March 5-10, 2023

CA Mehta, EG Kostadinova, DM Orlov, "Material Ablation During Entries into the Venusian Atmosphere", APS March Meeting, Las Vegas, NV, March 5-10, 2023

EG Kostadinova, CA Mehta, DM Orlov, "Ablation of carbon-based heat shield materials in Jupiter-like heating conditions", APS March Meeting, Las Vegas, NV, March 5-10, 2023

D.M. Orlov, E.G. Kostadinova, C.A. Mehta, I. Bykov, D.L. Rudakov, R. Smirnov and the DIII-D team, "Crossover of space exploration and fusion research: spacecraft heat shields and meteoroids in the DIII-D tokamak", AAPPS-DPP 2023, Port Messe Nagoya, Japan, Nov 12-17, 2023 (plenary)

EG Kostadinova and DM Orlov, "Exploring the crossover of space exploration and fusion research", NASA BPS Fundamental Physics Decadal Survey Workshop, May 2021 (online)

The research funded by this award were published in the US DoE Office of Science Research Highlights, APS DPP Highlights, and were covered by WIRED magazine article.

US DoE Office of Science Highlights, "Tokamak Experiments Provide Unique Data for Validating Spacecraft Heat Shield Ablation Models", https://science.osti.gov/fes/Highlights/2023/FES-2023-01-a

WIRED, Nov 15, 2021, https://www.wired.com/story/nuclear-fusion-spacecraft-jupiter/

ANS Nuclear NewsWire "DIII-D tokamak used to test spacecraft heat shield materials", Tue, Nov 16, 2021, https://www.ans.org/news/article-3438/diiid-tokamak-used-to-test-spacecraft-heat-shield-materials/

APS DPP Virtual Press Room, "Feeling the Heat: Fusion Reactors used to Test Spacecraft Heat Shields", November 2021, https://www.google.com/url?q=https%3A%2F%2Fhigherlogicdownload.s3.amazonaws.com%2FAPS%2Fb702bb59-ce08-4ebc-b70c-ab50811fa080%2FUploadedImages%2Fdocuments%2FVPR_2021%2FGA_Orlov_APS-DPP_2021.docx&sa=D&sntz=1&usg=AOvVaw3CRAyqyyzKaBNYAJEP3aPz