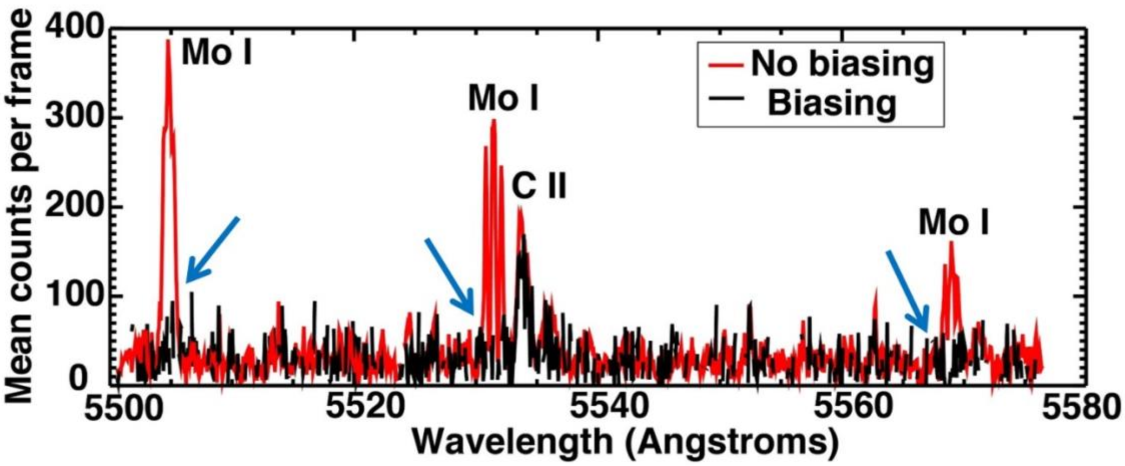
Understanding and Control of High-Z Material Erosion in Tokamaks with a Mixed-Materials Environment

Experiments at DIII-D National Fusion Facility and modeling reveal the important role of sheath potential and low-Z impurities in determining high-Z material erosion



Measured visible emission spectrum during the exposure of molybdenum (Mo) samples in the DIII-D tokamak, which indicates Mo erosion by divertor plasma. The spectrum has a range between 5550 Å and 5580 Å, in which three Mo I emission lines can be resolved. The red curve is from experiments without applying electrical biasing, while the black curve is with a positive biasing voltage. The Mo erosion disappears with positive biasing, demonstrating that the erosion was dramatically reduced.
Image courtesy of R. Ding, Institute of Plasma Physics, Chinese Academy of Sciences

The Science

Interactions between plasma and the surrounding wall materials of the tokamak are one of the key challenges in nuclear fusion research. Plasma-induced erosion of materials can significantly limit the lifetime of wall materials, and the eroded materials can be transported into the core plasma. Recent experiments on the DIII-D tokamak combined with modeling have deepened the physics understanding of high-Z material erosion and re-deposition in a mixed-materials environment, showing high potential for addressing this critical issue for fusion reactors.

Most erosion of high-Z materials is through physical sputtering by ion impingement. Researchers theorized that suppressing this sputtering process was essential to reduce erosion. Using thin-film samples, they determined that Mo erosion was strongly suppressed by using a positive biasing voltage to reduce the drop of electric potential across the sheath at the material surface. This slight positive voltage lowered the incident ion flux and energy, reducing Mo erosion by more than an order of magnitude. A high carbon impurity concentration in the background plasma, introduced by methane injection, was also found to reduce the net erosion rate of high-Z materials.

The Impact

High-Z materials will be used in the divertor of ITER and very likely in future fusion devices because of their low sputtering yields and low fuel retention compared to low-Z materials. The intrinsic disadvantage for high-Z materials is that large core radiation losses due to penetration of high-Z impurities may lead to poor plasma performance and restrict plasma operation.

To leverage the advantages of high-Z materials, it is essential to understand and control high-Z material erosion, which can help reduce high-Z impurity concentration in the core plasma and improve fusion performance. These results suggest that a relatively simple path exists toward reducing high-Z erosion, which may have significant implications for the active control of material erosion in future fusion reactors.

Summary

Dedicated experiments in the DIII-D tokamak coupled with modeling revealed that high-Z material erosion is strongly affected by low-Z impurity concentration in the plasma and the sheath potential, and can be actively controlled with electrical biasing and local gas puffing. The transport of low-Z carbon impurities not only dominates the physical sputtering source but also determines the overall erosion and deposition balance on the mixed-material surface.

Both experiments and modeling showed that high carbon impurity concentration in the plasma can reduce the net erosion rate of high-Z materials. The high local re-deposition of eroded materials is mainly controlled by the electric field and plasma density within the magnetic pre-sheath. These new findings have significant implications for the understanding and active control of W divertor target operation in ITER with its low-Z beryllium first wall.

Contact

Rui Ding
Institute of Plasma Physics, Chinese Academy of Sciences
rding@ipp.ac.cn

Funding

This work is based upon work supported by the US Department of Energy, Office of Science, Office of Fusion Energy Sciences and Office of Advanced Scientific Computing Research through the Scientific Discovery through Advanced Computing (SciDAC) project on Plasma-Surface Interactions, under Award No. DE-SC0018423, using the DIIID National Fusion Facility, a DOE Office of Science user facility, under Award No. DE-FC02-04ER54698. This work is partly supported by National Natural Science Foundation of China under Contract No 11675218.

Publications

R. Ding, *et al.,* “Advances in understanding of high-Z material erosion and re-deposition in low-Z wall environment in DIII-D,” Nucl. Fusion **57** 056016 (2017)

T. Abrams, *et al.,* “The inter-ELM tungsten erosion profile in DIII-D H-mode discharges and benchmarking with ERO+OEDGE modeling,” Nucl. Fusion **57** 056034 (2017)

R. Ding, *et al.,* “Simulation of gross and net erosion of high-Z materials in the DIII-D divertor,” Nucl. Fusion **56** 016021 (2017)