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Detection of Thermal Events Using Machine Learning for the Feedback Control of Thermal Loads in Wendelstein 7-X

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Wendelstein 7-X (W7-X) is the most advanced drift-optimized stellarator, designed to demonstrate the feasibility of the stellarator concept for a future fusion power plant with steady-state operation. Its primary goal is to prove quasi-steady-state operation with plasmas of up to 30 minutes in a reactor-relevant parameter regime. Achieving high-performance operation in W7-X and other fusion devices, such as ITER, necessitates an effective feedback control system for thermal loads, to prevent unnecessary plasma interruptions and ensure long-plasma operation. The feedback control system requires a high-level understanding of the thermal events, their type, cause, and risk, which is best achieved through advanced computer vision and machine learning techniques.

The development of an effective thermal load feedback control system for W7-X is slowed by challenges related to data generation and annotation in fusion. The complex and dynamic nature of thermal events, such as strike-lines, leading edges, hot spots, fast particle losses, surface layers, and reflections, makes it difficult to generate accurate and representative data for training machine learning models. Additionally, manual annotation of these events is a time-consuming and labor-intensive process, further complicating the development of a reliable and efficient dataset.

We propose an iterative strategy for thermal event detection using machine learning techniques. Our approach begins with the Max-tree algorithm, employed for semi-automatically annotating a small dataset, which facilitates hierarchical segmentation of thermal events while preserving the inclusion relationships among them. We then proceed to weakly supervised training of models for panoptic segmentation, utilizing the Mask R-CNN architecture with data from W7-X and WEST. Ultimately, our aim is to fine-tune large foundational models for segmentation and classification and implement transfer learning with synthetic data for accurate zero-shot thermal event detection in new devices, such as ITER. This approach ensures protection from day one, paving the way for the successful operation of future fusion power plants.

Speaker's Affiliation

Max-Planck-Institut für Plasmaphysik, Greifswald

Member State or IGO/NGO

Germany

Primary author: PUIG SITJES, Aleix (Max-Planck-Institut für Plasmaphysik)

Co-authors: JABŁONSKI, Bartłomiej (Lodz University of Technology, Department of Microelectronics and Computer Science, Łódź, Poland.); GRELIER, Erwan (CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France.); JAKUBOWSKI, Marcin (Max-Planck-Institut für Plasmaphysik, Greifswald, Germany.); MAKOWSKI, Dariusz (Lodz University of Technology, Department of Microelectronics and Computer Science, Łódź, Poland.); MITTEAU, Raphael (CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France.); GAO, Yu (Max-Planck-Institut für Plasmaphysik, Greifswald, Germany.)

Presenter: PUIG SITJES, Aleix (Max-Planck-Institut für Plasmaphysik)

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