Overview of the Wendelstein 7-X phase contrast imaging diagnostic

E. M. Edlund,[1,a)] M. Porkolab,[2] Z. Huang,[2] O. Grulke,[3,b)] L.-G. Böttger,[3,b)]
C. von Sehren,[3] and A. von Stechow[3]
[1]*SUNY Cortland, Cortland, New York 13045, USA*
[2]*MIT Plasma Science and Fusion Center, Cambridge, Massachusetts 02139, USA*
[3]*Max Planck Institute for Plasma Physics, Greifswald 17491, Germany*

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A phase contrast imaging (PCI) diagnostic has been developed for the Wendelstein 7-X (W7-X) stellarator. This diagnostic, funded by the U.S. Department of Energy through the Office of Fusion Energy Sciences, is a collaboration between the Max Planck Institute for Plasmaphysics, MIT, and SUNY Cortland. The primary motivation for the development of the PCI diagnostic is measurement of turbulent fluctuations, such as the ion temperature gradient, electron temperature gradient, and the trapped electron mode instabilities. Understanding how the magnetic geometry and other externally controllable parameters, such as the fueling method and heating scheme, modify the amplitude and spectrum of turbulence is important for finding operational scenarios that can lead to improved performance at fusion-relevant temperatures and densities. The PCI system is also sensitive to coherent fluctuations, as may arise from Alfvén eigenmodes or other MHD activity, for example. The PCI method creates an image of line-integrated variations in the index of refraction. For a plasma, the image created is proportional to the line-integral of electron density fluctuations. This paper provides an overview of some key features of the hardware and the optical system and presents two examples of recent measurements from the W7-X OP1.2a experimental campaign. *Published by AIP Publishing.*
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I. INTRODUCTION

Phase contrast imaging (PCI) diagnostics have been used on a number of magnetic confinement machines, including the TCA,[1] DIII-D,[2] Alcator C-Mod,[3] and Tokamak à Configuration Variable (TCV)[4] tokamaks and also on the Large Helical Device (LHD) stellarator.[5] Installation of the PCI hardware on W7-X was completed in the summer of 2017, and the first operation of the diagnostic occurred in September of 2017 during the OP1.2a campaign.[6]

The W7-X stellarator is a large-scale fusion experiment that began operation in late 2015[7,8] and recently concluded its second operational phase, OP1.2a, that ran from September 5 to December 7 of 2017. The average major and minor radii of W7-X are 5.5 m and 0.53 m, respectively. W7-X is of the Helias line of stellarators, with a nearly quasi-isodynamic magnetic field geometry at high β (where $\beta \sim p/4\mu_0 B^2$), and was designed with consideration given to seven engineering and physics constraints, including low neoclassical losses of particles and energy and low bootstrap current.[9] The ability to vary the coil currents provides external control over the mirror ratio, rotational transform, and the position of the magnetic axis. One of the major goals of the W7-X research program is to understand the impact of the magnetic field configuration on global performance through its influence on both neoclassical and turbulent transport. One of the primary goals of the W7-X PCI diagnostic is to help assess the nature of turbulence and its impact on global transport, especially as it relates to the magnetic configuration.

The ISS_{04} scaling, which describes the multi-parameter scaling for stellarator energy confinement times, indicates that high-performance plasmas in W7-X should greatly exceed the performance of all previous stellarators and approach that of similarly sized tokamaks.[10] Analysis of experiments from the W7-X OP1.1 campaign indicates performance congruent with the $ISS_0 4$ scaling[8] though these energy confinement times are still about an order of magnitude smaller than the best tokamak H-mode energy confinement times.

One of the outstanding points of uncertainty in our predictive capability, applying to higher performance scenarios in W7-X and upcoming next-generation devices like ITER, is how turbulent transport will scale as we move to larger devices and higher temperatures and densities. A variety of turbulent mechanisms, including the ion temperature gradient (ITG) instability, the electron temperature gradient (ETG) instability, and the trapped electron mode (TEM) instability, are expected to modify the transport and energy confinement properties of these plasmas.[11,12] This is an important area of research to address in anticipation of future burning plasma experiments that will be dominated by electron-heating. Electromagnetic modes, such as kinetic ballooning modes[13] and Alfvén eigenmodes,[14] may also modify the transport of the bulk plasma or energetic components. The role of the magnetic field geometry on turbulence and instabilities, and therefore the

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a)eric.edlund@cortland.edu
b)Also affiliated with the Technical University of Denmark, Kongens Lyngby, Denmark.