Towards high performance operation of the HSX stellarator

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Abstract

This overview paper details recent upgrades and enhancements to the HSX stellarator experiment. A new 70 GHz gyrotron is being commissioned, capable of delivering 300 kW of power for 100 ms, enabling operation at densities around 2 x 10^{19} m^{-3}. To support the required 1.25 T operation, the coil system has undergone significant improvements, including enhanced alignment and reinforced supports. Additionally, the plasma-facing components have been cleaned to prepare for high-power operation, resulting in plasmas with minimal impurity content. The diagnostic suite of HSX has also seen substantial upgrades, with the installation of a 400 Hz Thomson Scattering system, a novel wide-range spectroscopy system, and enhancements to the ECE and reflectometry diagnostics. Additionally, a series of optimized magnetic field configurations is being investigated that are predicted to maintain excellent quasi-symmetry while reducing turbulence, thereby enhancing plasma performance in the HSX stellarator.

Introduction

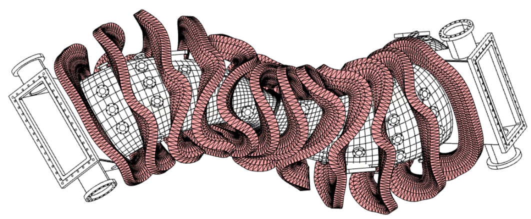

Figure 1: CAD rendering of one period of HSX showing 12 of its 48 3D shaped coils.

The Helically Symmetric Experiment (HSX) is a midsize stellarator with major and minor radii of 1.2 m and 0.12 m, respectively [1]. The experiment utilizes 48 non-planar magnetic field coils to generate a quasi-symmetric magnetic field of approximately 1 T, which confines plasmas with core electron temperatures exceeding 2 keV. Due to its neoclassical transport optimization, HSX's heat and particle confinement is primarily limited by anomalous transport, particularly Trapped Electron Mode (TEM) turbulence [2]. Additionally, HSX plasmas exhibit significant flows in a direction of symmetry, enabling detailed studies of the interaction between turbulence and flows [3]. However, research of ion temperature gradient-driven modes and flows has been constrained by a substantial background neutral population and cold ions. This is attributed to low-density operation mandated by the cut-off of the employed 28 GHz gyrotron, resulting in relatively long neutral penetration lengths and poor coupling between heated electrons and ions.

70 GHz ECRH

A 70 GHz system is being installed at HSX to enable operation at four times higher densities. This new system features a CPI gyrotron, operating in a depressed collector scheme with an output power of 300 kW. The gyrotron has been installed at HSX and connected to a new 60 kV power supply system, which uses a set of capacitors to provide power for 100 ms long plasmas. Corrugated, oversized waveguides transmit the mm-wave radiation to the HSX experiment, with installation completion expected later this year. With the new gyrotron, plasmas can be heated using the X2 heating scheme, which offers excellent absorption characteristics and allows for plasma operations at densities up to 2 x 10^{19} m^{-3} without significant beam refraction. According to the ISS04 scaling law predicting stellarator confinement times, electron temperatures of 2 keV will be achieved in HSX during high-density operation. This not only supports higher ion temperatures (>100 eV) and reduced neutral background densities but also increases the plasma beta, potentially leading to the observation of additional plasma instabilities.

Improved Coil system

The 70 GHz system requires a magnetic field of 1.25 T, prompting an overhaul of the HSX coil system. Although HSX was initially designed for 1.37 T, it has never operated significantly above 1 T. This overhaul includes stiffening the coil supports as suggested by ANSYS modeling. Support clamps have been installed at 24 locations to secure the 3D-shaped copper coils of HSX. Additionally, the 3D coil geometry has been re-evaluated using high-precision positional measurements, and deviations have been systematically documented and corrected to ensure the coils are positioned within 2 mm tolerances.

Plasma wall interaction

The HSX plasma-facing components have been prepared for the increased heating power and discharge duration provided by the new gyrotron. Previously, plasma density control at HSX was complicated by the accumulation of dust and flakes from 20 years of wall conditioning involving carbonizations and boronizations and it was anticipated that high-power operation would exacerbate these challenges. Therefore, the plasma vessel was thoroughly cleaned, leak-checked, and baked using a newly installed heating system. This resulted in excellent vacuum conditions in the 10^{-8} torr range and clean plasma conditions, with oxygen, and nitrogen emission lines almost absent in recorded spectra. The cleaner plasma facing surfaces are being leveraged to study the effects of different ion species composition on turbulent and coherent density fluctuations [6].

Diagnostic upgrades

To enhance the device's capability for studying turbulent heat and particle transport, the Thomson scattering system of HSX has undergone a significant upgrade. A state-of-the-art Nd:YAG laser, capable of operating at a repetition rate of 400 Hz with a pulse energy of 1 Joule, has been installed, commissioned, and successfully operated. Additionally, newly designed amplifiers [4] and an advanced optical setup [5] have been implemented to support the high pulse-rate laser and further improve the signal-to-noise ratio of the measurements. This successful upgrade makes the Thomson Scattering system one of the most advanced of its kind, significantly enhancing the diagnostic capabilities of HSX. Furthermore, a new fast survey spectrometer has been designed, installed, and commissioned at HSX. The system offers an unprecedented combination of spectral resolution, spectral range, and photon throughput. This new spectrometer is being used to study impurity emissions, as well as hydrogen and helium concentrations. In addition, the ECE and reflectometry systems of HSX have undergone substantial upgrades to be compatible with 70 GHz ECRH and to further improve the signal-to-noise ratio. These enhancements have allowed for the clear identification of modes and instabilities in HSX plasmas.

Improved configurations

To further enhance the performance of the HSX stellarator, new configurations are being explored that may mitigate Trapped Electron Mode (TEM) turbulence while maintaining excellent neoclassical confinement. These configurations have been identified using a database approach [7], revealing that elongating plasmas in HSX can significantly reduce the linear growth rates of TEMs by broadening the magnetic wells experienced along magnetic field lines. Initial results from successful elongated plasma discharges will be presented, along with comparisons to non-linear simulations using the GENE flux-tube and GENE 3D codes.

Conclusion

The HSX stellarator experiment is advancing towards high-performance plasma operation, thanks to the new 70 GHz ECRH system, enhanced plasma diagnostics, and an integrated experimental and computational program focused on turbulence-optimized configurations. As the world's only quasi-helically symmetric device and the world's most advanced quasi-symmetric stellarator, HSX plays a crucial role in advancing the understanding of 3D plasmas, turbulence, and flows, thereby supporting the physics basis for next-step fusion power plants.

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