Analysis of Wendelstein 7-X divertor load symmetrization

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The Wendelstein 7-X (W7-X) stellarator recently conducted its first experimental campaign with an uncooled divertor allowing achievement of pulse lengths exceeding 25 s and stored energies exceeding 1 MJ. In order to achieve this level of performance, the heat loads on the ten divertor modules needed to be symmetrized. In the previous limiter campaign on W7-X, the presence of error fields, magnetic fields whose presence results in divertor heat load asymmetries, was determined to be small and correctible through flux surface mapping [1, 2, 3]. Such work also confirmed the high level of accuracy with which the experiment was built and assembled [4]. In preparation for this first divertor campaign, flux surface mapping was used to directly assess the \( n/m = 1/1 \) error field and demonstrate compensation. It is this harmonic of the error field which resonates with the \( n/m = 5/5 \) edge island chain resulting in mis-loading of divertor modules. The effect of electromagnetic deformations of the superconducting coils resulted in a 2% reduction in rotational transform. This results in around a \( \sim 5 \text{ cm} \) shift in the edge island chain which was corrected using the planar superconducting coils. Measurements of divertor thermal loads was made possible through thermocouples embedded in the divertor modules and an IR camera system. Phase and amplitude (compass) scans using the copper trim coil system allowed determination of the divertor heat load symmetrizing trim coil settings, and confirmed the measurements made with

![Figure 1: Flux surface images of the ‘high-iota’ configuration showing the helical axis deformation. Black lines depict measured flux surface, red lines are simulated data. Axis shift of 74 pixels corresponds to approximately 12 cm.](image-url)
Before the beginning of plasma operation, the flux surfaces of the W7-X stellarator were mapped using a technique called flux surface mapping. In this technique an electron beam emitter is positioned in the vacuum vessel while a swept fluorescent rod is imaged, creating a trace of the field lines on which the electrons are launched [5]. This is possible in a stellarator since it possess vacuum magnetic flux surfaces (unlike a tokamak). In addition to repeating measurements made before the previous limiter campaign, a new ‘high-iota’ configuration was mapped. This configuration places the rotational transform near $\iota = 1$ on the magnetic axis and has a $n/m = 5/4$ edge island chain. As a result of the low magnetic shear nature, this configuration is sensitive to $n/m = 1/1$ magnetic fields, specifically the magnetic axis becomes helically deformed. In figure 1 the presence of this helical shift is shown. Such a helical shift was corrected by energizing the trim coils in an $n = 1$ pattern, where the peak coil current was 134 A at a phase of 180° relative to the module one coil. Amplitude measurements are in good agreement with estimates based on measurements made in the limiter campaign. A deviation in corrective phase can be attributed to electromagnetic load effects. Additionally, measurements made in the first campaign were done at low field. The level of corrective field is in agreement with electromagnetic deformation models of the superconducting coils (using the measured coil geometry).

The effect of electromagnetic loads on rotational transform were well documented in the first limiter campaign were the position of the $n/m = 5/6$ island chain was measured as a function of field strength. In the limiter configuration it was found that this island chain was located radially inside of it’s ideal position at low field, moving into the ideal position as 2.5 T was approached. Such a behavior is well understood in terms of non-planar coils. Here, the self-force of a non-planar coils pushes the coil toward a more planar and round shape. The net effect of which is to re-duce the coils contribution to the rotational transform. Operation of configurations with a

Figure 2: Field line diffusion simulation of scraper element heat loads using the AEK51 camera view and uncorrected magnetic fields. Loads on the scraper should go to zero when iota is correctly adjusted.
$n/m = 5/5$ island chain suggested that iota was in fact reduced by as much as 2%, as predicted by modeling. A correction of approximately $-700 \, A$ of planar coil current was necessary to move the edge island chain radially inward, giving a divertor load pattern more consistent with simulation results. This also avoided interactions of the edge island structure with protruding uncooled wall structures. Meanwhile the high-iota exhibited a slightly increased iota from the nominal value. This change in load character of the coil-set can be attributed to a complex interaction between the planar and non-planar superconducting coils. In the high-iota the planar coils are energized with $-10.2 \, kA$ of current while the limiter configuration has $+5 \, kA$ of current. In the next experimental campaign, the scraper elements will provide a key metric for correction of this effect. Simulations with electromagnetically deformed coils predict that if left uncorrected, heat loads will appear on the scraper (figure 2). By adjusting the rotational transform until this effect disappears, the edge rotational transform can be more finely tuned.

In order to avoid overloading of divertor modules, symmetrizing magnetic fields were applied, allowing pulse lengths exceeding 25 seconds. A technique known as a compass scan was performed using the trim coils to determine the corrective field. In this technique, discharges are repeated with different phases and amplitudes of an $n = 1$ trim coil perturbation. The divertor thermocouple temperature rise was then utilized as a proxy for the heat flux. In this way a map of divertor temperature rise asymmetry could be made and by fitting a two dimensional parabola to the data. The configuration which minimized divertor load asymmetries could be determined and tested. This method was successful in determining the correcting error field in two divertor configurations. Figure 3 depicts the results of such a scan. Here each circle represents a separate 2 $MW$, 2 $s$ discharge. For each discharge, the maximum thermocouple temperature rise in the 120 seconds after the discharge is recorded. The range of maximum divertor module temperature rises is then calculated for each discharge. Symmetry is achieved

Figure 3: Compass scan of the standard magnetic configuration. White circles indicate trim coil phases and amplitudes, while the color map is the fit of a two-dimensional paraboloid to the data at those points. A symmetrizing trim coil configuration of $98 \, A @ 162^\circ$ is found.
when the range of maximum temperature rises goes to zero. Initial comparisons with infrared camera data have begun to confirm this method as accurate for correcting the $n = 1$ asymmetry in the experiment [6]. Future experiments will attempt to examine multiple coil phases and amplitudes in a single shot, relying in infrared data for the assessment.

The first divertor campaign in W7-X has allowed direct assessment of the effect of error fields on divertor operation, along with their compensation by perturbative trim coils. Flux surface measurements of the ‘high-iota’ configuration confirmed the phase and amplitude of the $n/m = 1/1$ component of the error field. These measurements were in agreement with earlier measurements made using the $t = 1/2$ configuration. Electromagnetic loads on the superconducting coils resulted in an 2% decrease in iota, an effect which was compensated using the planar superconducting coils. A compass-scan technique was used to determine the divertor heat load symmetrizing trim coil magnetic field in multiple configurations. This in turn allowed pulse lengths exceeding 25 s.

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