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Confirmation of the magnetic topology of W7-X

The ability to control edge magnetic topology is of great interest to the magnetic-confinement fusion community. The Wendelstein 7-X (W7-X) stellarator (in Greifswald, Germany) is no exception to this statement; simulations have suggested that unwanted stray magnetic fields (error fields) may degrade the performance of its island divertor. Specifically, magnetic fields with Fourier harmonics of m/n = 1/1 resonate with the m/n = 5/5 island divertor, breaking its five-fold stellarator symmetry. Although the first experimental campaign (OP1.1) on W7-X did not directly address the m/n = 1/1 error field, efforts were made to begin to address the possible presence of error fields with n = 1 character. In the article "Confirmation of the topology of the Wendelstein 7-X magnetic field to better than 1:100,000" (published November 30, 2016 in *Nature Communications* [1]), key results from flux surface measurements of W7-X are described. These are under a Creative Commons license, which allows them to be reproduced if credit is appropriately given. The article itself is open access and can be found here: http://www.nature.com/articles/ncomms13493.

That article describes flux surface measurements of the W7-X OP1.1 configuration, and of a special configuration with iota near 0.5 which was used to determine the amplitude and phase of the n = 1, m = 2 field error. More measurements and details can be found in the papers by Otte et al. [2] and Lazerson et al. [3].

Island chains and error fields

An island chain can appear on any magnetic surface with a rational value of iota. In practice, island chains with a detectable and operation-relevant size appear only for low-order rational values of iota, and only if there is a Fourier component of the magnetic field that has matching (i.e., resonant) toroidal and poloidal mode numbers, n and m, so that $\iota = n/m$.

W7-X is designed to reach iota of 1 at the outermost flux surface in the main configuration. It is a five-fold periodic device, with a pentagon-like shape, and has an n = 5 Fourier component to its magnetic field, so that an $n = m = 5$ island chain appears at the plasma edge, this island chain is used in W7-X to establish an island divertor for particle and power exhaust, a crucially important part of a fusion device.

The quality of these islands is thus very important for the success of the project. Unwanted error fields may break the 5/5 islands and limit the operation capabilities of the device. We describe these error fields in relative terms, $b_{mn}= B_{mn}/B_0$, where B_0 is the average magnetic field strength in the confinement region, and B_{mn} is the amplitude of the m, n Fourier component of the error field. In the search for error fields, we focus on the toroidal (n) numbers since only n = 5 and multiples thereof should be present, whereas a broad spectrum of poloidal (m) numbers is present in W7-X.

Of particular concern is the n = 1 component, which would create an n/m = 1/1 island chain; this could result from, e.g., a slightly misplaced coil module and would lead to asymmetric divertor loading.

In this issue . . .

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How we measured the error field

Island chains are sensitive indicators of small changes in the magnetic field topology, since they are physical manifestations of resonances in the magnetic topology. The radial full width w of an island chain is related to a resonant magnetic field component through [4]

$$b_{mn} = \frac{\mathrm{d}\iota}{\mathrm{d}r}\frac{w^2 m}{16R_0} \Leftrightarrow w = 4\sqrt{\frac{R_0 b_{mn}}{m\frac{\mathrm{d}\iota}{\mathrm{d}r}}} \qquad (1)$$

For the configuration chosen for error field studies here, iota is nearly constant from the inner to the outer magnetic surfaces, so a sizable island chain will result from even a very small resonant error field. See Fig. 1.

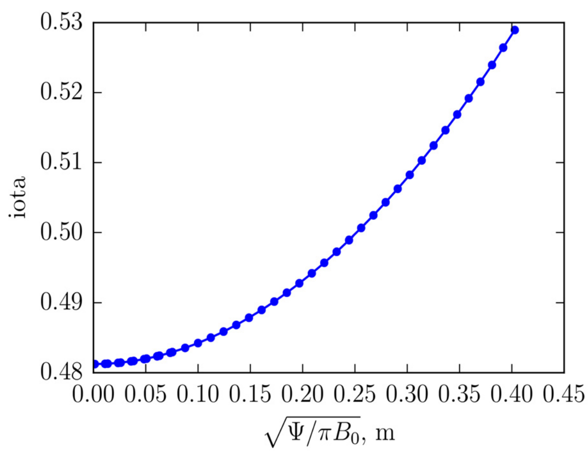

Fig 1. The iota profile is shown for the special configuration developed for field error detection. Iota varies only minimally around the resonant value of 1/2. The x-axis is a measure of the minor radial size (in meters) of the magnetic flux surface, i.e., a pseudo-radial coordinate. Source: *Nature Communications* [1].

In the complete absence of error fields, a small $n = 5$, $m = 10$ island chain would appear at the iota = 1/2 location at a distance of around 25 cm from the innermost magnetic surface, but in the presence of even a small $n = 1$ error field, an $n = 1$, $m = 2$ island chain will appear.

The B_{21} error field is too small to create an island structure large enough to be measured clearly. This is in part due to the good news that it is small, and in part due to iota being so close to 1/2 that the electron beam comes very close to its launch position (the electron gun) after two toroidal transits, thus running the risk of hitting the back of the electron gun and disappearing. Such shadowing effects are well-known nuisances and are particularly severe near rational values of iota. We have a new electron gun design for OP1.2 that should minimize this problem.

It was nevertheless possible to indirectly measure the B_{21} field error, despite this shadowing problem, by adding an $n = 1$ error field with a well-defined amplitude and phase, using the set of five trim coils [5]. The primary purpose of these coils is to trim away the unwanted $n = 1$ error field components, but the trim coils are used here to create an extra $n = 1$ error field and thus generate an $n/m = 1/2$ island chain wide enough to be measurable.

By scanning the phase and amplitude of the imposed, well-defined error field, measuring the island phase and width (Fig. 2), and comparing to Eq. (1), we find that an $n/m = 1/2$ island with a width of about 4 cm must be present, even in the absence of trim-coil-induced fields.

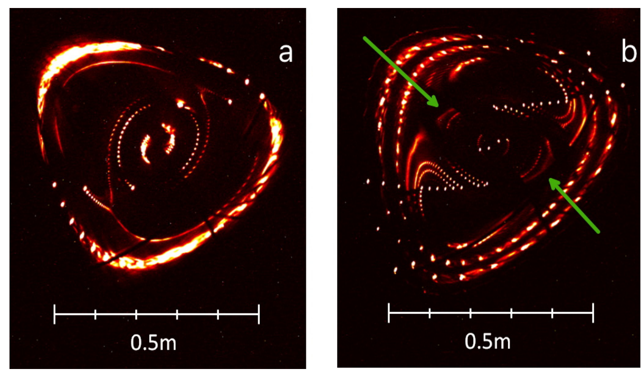

Fig. 2. Measured island chains for different coil current settings. For the special iota ~ 1/2 configuration, the $n = 1$, $m = 2$ island size and phase was measured with the standard fluorescent rod flux surface measurement technique. Here two conglomerate images with several nested surfaces are shown for two different phases of a purposely added $n = 1$ field structure with the same amplitude. Although the shadowing problem leads to gaps, the trained eye can still detect the changes in size and phase of the $m = 2$ island. In part b) evidence of a smaller $n = 2$, $m = 4$ structure can be seen as well, indicated with green arrows. Source: *Nature Communications* [1] (slightly augmented version of the published figure).

Entering the other known quantities for this configuration we arrive at:

$$b_{21} = \frac{\mathrm{d}\iota}{\mathrm{d}r}\frac{w^2 m}{16R_0} = 0.15\mathrm{m}^{-1}\left(\frac{(0.04\mathrm{m})^2 \cdot 2}{16 \cdot 5.5\mathrm{m}}\right) = 5.4 \times 10^{-6}$$

To our knowledge, this is an unprecedented accuracy, both in terms of the as-built engineering of a fusion device, as well as in the measurement of magnetic topology. This value is well within the range that can be corrected with the trim coils.

The as-built coil forms and their as-installed locations have been implemented numerically in our codes and used to calculate the size, phase, and location of the intrinsic 1/2 island chain resulting from the B_{21} component. These data agree very well with our fully independent direct measurements of the magnetic topology. The agreement regarding amplitude is shown in Fig. 3.

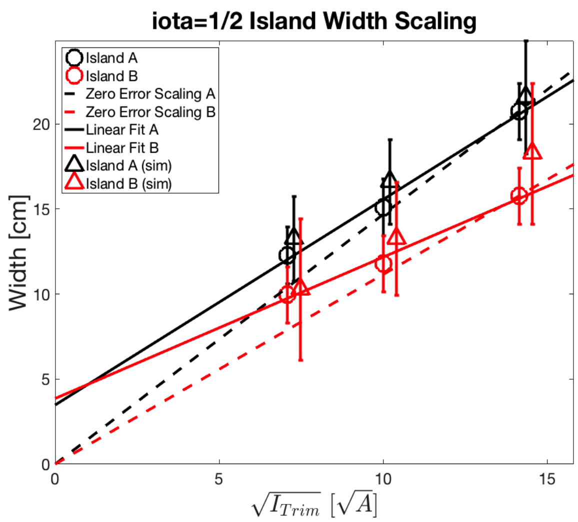

Fig. 3. The measured island widths (circles) are compared directly to those predicted from numerical calculations that take the as-built, as-installed geometry of the W7-X coil set into account (triangles). Excellent agreement is seen. The offset from zero in the linear fits indicates the intrinsic 4 cm island width. If no intrinsic error field were present, the points would line up with the dotted lines. Source: *Nature Communications* [1].

The now experimentally validated numerical model of the coil system allows us to identify the primary source of the measured error field: It is caused primarily by imperfections in the placement and shapes of the planar coils. For the special magnetic configuration chosen here, the planar coils produce a much larger fraction of the magnetic field than they do in configurations used for plasma operation; this is because iota, which is generated only by the non-planar coils, was lowered so dramatically. The W7-X standard configuration has iota = 1 at the plasma edge and has no planar coil current. At first glance, one may argue that what we measured is not directly related to the error fields for later operation in the standard configuration and hence not particularly relevant. But what we measured is highly relevant because it confirms the metrology measurements to a very high accuracy. These measurements tell us that the b_{11} relative error caused by imperfections in the magnetic coil system is also expected to be small, likely close to or somewhat below a previous metrology-based estimate of 1.1×10^{-4}, which is also well within the correction capabilities of the trim coils. Moreover, it is an independent confirmation of what we already expected from metrology measurements: That W7-X was built with the required accuracy.

Of course, we plan to measure the b_{11} error field in OP1.2, in a configuration with iota near 1, whose magnetic field is overwhelmingly dominated by the nonplanar coils and is very close to those that are used for plasma operation [5].

Erratum for *Nature Communications* paper

In the *Nature Communications* paper (but not here), there were a few typos and typesetting errors in the text and the affiliations in the W7-X team; the author affiliations were corrected on line after publication in an erratum [6]. Of note: there are unfortunately a few instances where B_{mn} was written but b_{mn} was meant. These remain in the paper, as it was not practical to correct them given the rules for such corrections in Nature journals, and it is clear from the context which of the two terms was meant.

[1] T. Sunn Pedersen et al., Confirmation of the topology of the Wendelstein 7-X magnetic field to better than 1:100,000, *Nature Commun.* 7, 13493 (2016).

[2] M. Otte et al., Setup and Initial Results from the Magnetic Flux Surface Diagnostics at Wendelstein 7-X, *Plasma Phys. Contr. Fusion* **58**, 064003 (2016).

[3] S. Lazerson et al., First measurements of error fields on W7-X using flux surface mapping, *Nucl. Fusion* **56**, 106005 (2016).

[4] A. H. Boozer, Non-axisymmetric magnetic fields and toroidal plasma confinement, *Nucl. Fusion* **55**, 025001 (2015).

[5] S. A. Bozhenkov et al., Methods for measuring 1/1 error field in Wendelstein 7-X stellarator, *Nucl. Fusion* **56**, 076002 (2016).

[6] T. Sunn Pedersen et al., Erratum: Confirmation of the topology of the Wendelstein 7-X magnetic field to better than 1:100,000, *Nature Commun.* **8**, 14491 (2017)

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On behalf of our co-authors and the W7-X Team

The new era has begun: The first deuterium plasma in LHD on March 7, 2017

The Large Helical Device (LHD) launched its new phase of research with deuterium plasmas on March 7, 2017, after several years of preparation not only for device upgrades but also for administrative procedures.

A commemorative ceremony was held on March 7, 2017, with approximately 150 guests [including members of the Diet, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), local governments, local residents' associations, NIFS collaborators, and other people] in attendance.

The Director General of NIFS, Prof. Yasuhiko Takeiri, delivered the ceremonial address, followed by the initiation of the sequence by pushing the button to successfully produce the first deuterium plasma heated by ECH. By the way, the button had been kept from the ceremony for the first plasma of LHD conducted in March 1998.

The first light of the deuterium plasma is shown in Fig. 1, and its waveform (much simplified from a usual waveform of LHD, for the purpose of the ceremony) is shown in Fig. 2.

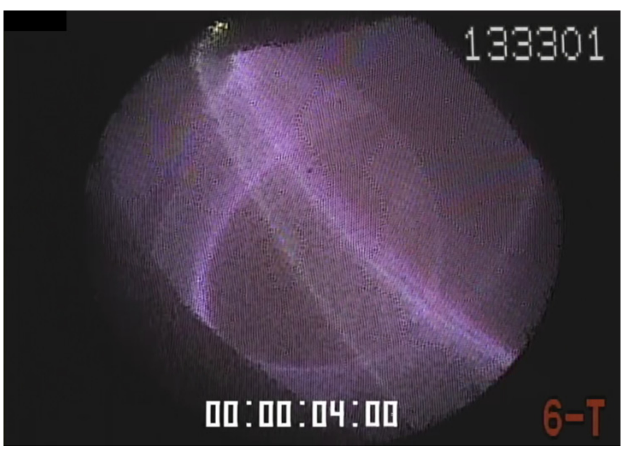

Fig. 1. The first deuterium plasma in LHD (#133301).

After the successful production of the first deuterium plasma, the Kusudama, a decorative paper ball for festive occasions in Japan, was opened collaboratively by distinguished guests (Fig. 3). The vertical banner reads, "Celebration (in red): Deuterium first plasma production." The congratulatory speeches continued, including a speech by Dr. David Gates (Princeton Plasma Physics Laboratory); congratulatory messages from distinguished international collaborators were introduced.

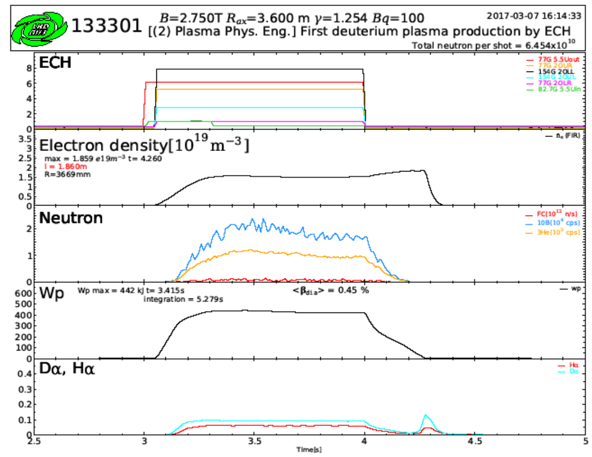

Fig. 2. A waveform of the first deuterium plasma.

In the deuterium experiment in LHD, higher performance of plasma confinement is envisaged, and further advanced research will be conducted to facilitate not only helical systems research but also worldwide fusion research. We appreciate your further support and interest, and invite you to utilize the LHD as one of the major advanced international platforms for fruitful collaborative research.

Fig. 3. Opening of the "Kusudama."

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