Configuration scan experiments in the latest experimental campaign of Wendelstein 7-X stellarator

T. Andreeva[1], A. Alonso[2], C.D. Beidler[1], S. Bozhenkov[1], C. Brandt[1], N. Chaudhary[1], A. Dinklage[1], T. Estrada[2], G. Fuchert[1], J. Geiger[1], O. Grulke[1], M. Hirsch[1], C. Killer[1], T. Klinger[1], A. Krämer-Flecken[3], S. Lazerson[1], C. Nührenberg[1], K. Rahbarnia[1], A. v. Stechow[1], H. Thomsen[1], J.C. Schmitt[4], M. Wappl[1], Th. Wegner[1], G. Wurden[5], and the W7-X Team

[1]*Max Planck Institute for Plasma Physics, Wendelsteinstr. 1, 17491 Greifswald, Germany*
[2]*LaboratorioNacional de Fusi´on, CIEMAT,28040 Madrid, Spain*
[3] *Institute for Climate and Energy Research – Plasma Physics, Forschungszentrum Jülich, 52425 Jülich, Germany*
[4]*Type One Energy Group, United States of America*
[5]*Los Alamos National Laboratory, Los Alamos, NM, 87545, USA*

Introduction

Wendelstein 7-X (W7-X) is an advanced stellarator, which uses the modular coil concept to realize magnetic configurations optimized for fusion-relevant plasma properties [1]. The machine went into operation in December 2015 at the Max-Planck-Institut für Plasmaphysik in Greifswald, Germany. The latest experimental campaign (OP2.1) was conducted from November 2022 to March 2023. Configuration scans performed in the previous W7-X experimental phase (OP1.2b) between Standard and High iota magnetic configurations by the gradual successive variation of the rotational transform, revealed an unexpected increase of the plasma confinement time in the intermediate limiter configurations [2]. The confinement improvement was accompanied by MHD-activity, termed ILMs, observed by several diagnostics [3]. Experiments performed in OP2.1 aimed to confirm observations from OP1.2b with a full set of diagnostics, complementing the scanned configuration space with new magnetic configurations.

OP2.1 iota scan sessions

Configurational scans reported in this paper were conducted in OP2.1 between Standard and High iota magnetic configurations (HI-scan) as well as between Standard and Low iota magnetic configurations (LI-scan). Reference Standard (EJM001), Low iota (DBM001) and High iota (FTM007) configurations have, respectively, five, six and four islands outside the last closed magnetic surface (LCMS) and are characterized by $\iota/2\pi$=5/5, 5/6 and 5/4, respectively. Fig. 1 represents corresponding Poincaré plots. Each of both scans consisted of 14 different configurations, where each intermediate configuration is characterized by equal coil currents in the non-planar coils (NPCs) and by equal coil currents in the planar coils (PCs), see Table 1. The change in the rotational transform was produced by systematical variation of the ratio of the PC-currents to the NPC-currents, serving as the normalized figure of merit distinguishing the different configurations in each scan. Trim coils were also used in these experiments to compensate a 1/1-error field component intrinsic to the coil system due to unavoidable fabrication and assembly inaccuracies as it was done in OP1.2b scan [2]. Input discharge parameters were kept identical in all configuration scans: the ECRH power and the line-integrated electron density were targeted at P_{ECRH} =2 MW and $\int n_e dl$ =$3.5{\cdot}10^{19}$ m^{-2}, respectively. In each discharge power modulation was applied in the time range from 3 s to 4 s to enable heat pulse studies [4]. In addition, the third iota scan session was conducted in the subset of intermediate, most promising configurations of HI-scan. In this last iota scan session the high performance discharges were one of the main session aims.

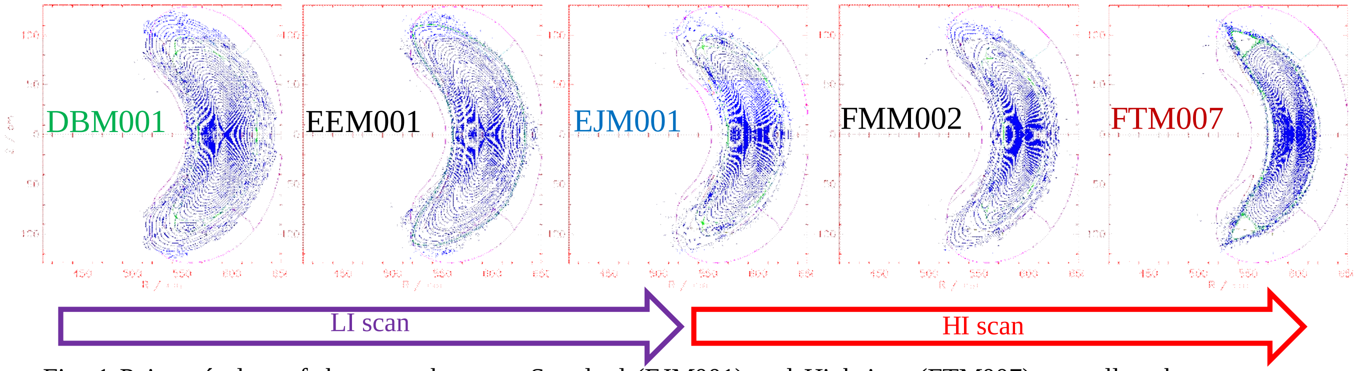

Fig. 1 Poincaré plots of the scans between Standard (EJM001) and High iota (FTM007) as well as between Standard (EJM001) and Low iota (DBM001) configurations.

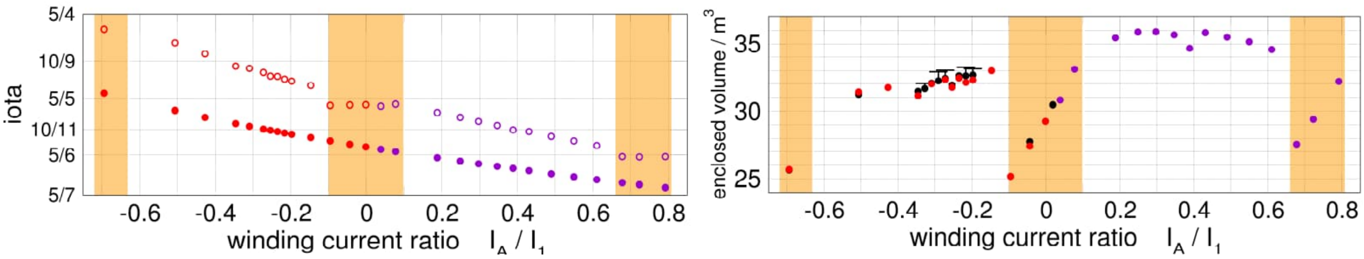

Fig. 2 Iota values (left plot) and volumes of scanned configurations (right plot) of the OP2.1 scans. Iota values were calculated from the field line tracing. Filled circles indicate the central value of iota ι_0, empty circles – iota at the boundary ι_b..Red color corresponds to HI scan, violet – to LI scan. Black points on the figure representing volumes show OP1.2b configurations for a comparison.

ST-HI	20221214	Name in DB	NPC exp	PC exp	corr	PC_corr.	current ratio	ST-LI	20230126	Name in DB	NPC exp	PC exp	corr	PC_corr.	current ratio
1	20221214.13	EJM001+2520	13046	-500	483	-17	-0.04	1	20230126.5	EIM005+2520	12989	0	500	500	0.00
2	20221214.21	EJM008+2520	13114	-1040	465	-575	-0.08	2	20230126.13	EIM004+2520	12922	500	500	1000	0.04
3	20221214.22	FKM003+2520	13196	-1707	443	-1264	-0.13	3	20230126.14	EHM003+2520	12748	1897	500	2397	0.15
4	20221214.23	FLM002+2520	13279	-2374	421	-1953	-0.18	4	20230126.16	EGM000+2520	12654	2647	500	3147	0.21
5	20221214.24	FLM000+2520	13361	-3040	399	-2641	-0.23	5	20230126.17	EFM002+2520	12579	3240	500	3740	0.26
6	20221214.25	FMM003+2520	13392	-3290	391	-2899	-0.25	6	20230126.18	EFM001+2520	12505	3835	500	4335	0.31
7	20221214.28	FMM002+2520	13423	-3540	382	-3158	-0.26	7	20230126.19	EEM003+2520	12442	4335	500	4835	0.35
8	20221214.39	FMM001+2520	13454	-3790	374	-3416	-0.28	8	20230126.20	EEM001+2520	12379	4835	500	5335	0.39
9	20221214.40	FMM000+2520	13485	-4040	366	-3674	-0.30	9	20230126.26	EDM000+2520	12292	5520	500	6020	0.45
10	20221214.43	FNM001+2520	13546	-4540	349	-4191	-0.34	10	20230126.28	EDM001+2520	12205	6208	500	6708	0.51
11	20221214.44	FOM004+2520	13608	-5040	333	-4707	-0.37	11	20230126.30	ECM007+2520	12118	6897	500	7397	0.57
12	20221214.45	FPM004+2520	13746	-6165	295	-5870	-0.45	12	20230126.31	ECM008+2520	12022	7647	500	8147	0.64
13	20221214.46	FQM001+2520	13883	-7290	258	-7032	-0.53	13	20230126.42	EBM007+2520	11959	8147	500	8647	0.68
14	20221214.47	FTM007+2520	14219	-10040	167	-9873	-0.71	14	20230126.43	DBM001+2520	11863	8895	500	9395	0.75

Table. 1 Characteristics of configurations in the OP2.1 iota scans: configuration experimental IDs, configuration names according to the W7-X internal specification, NPC and PC winding-currents in Ampere, PC current corrections, adjusted PC winding currents and coil current ratio PC/NPC. Divertor configurations are marked in orange, limiter configurations – in white, in consistence with Fig.2 and 3. The adjustments of the PC currents were performed to compensate for the iota-effect due to the elastic coil deformations caused by the electro-magnetic forces in the as-built coil geometries in order to restore the as-designed magnetic fields [5]. In all calculations with as-designed coil geometries corrected PC currents were used.

Experimental observations and first results

The main parameter used for characterizing the plasma confinement during configuration scans was the diamagnetic energy. As observed previously in OP1.2b intermediate magnetic configurations in HI-scan were characterized by an increased confinement [2]. Fig. 3 demonstrates normalized diamagnetic energy, measured in both scans. Normalization was performed in order to mitigate the effect of a changing volume of configurations (a larger volume with the same profiles on this volume results in a larger energy) and subtle variations in the experimental conditions w.r.t. line-integrated electron density (the ECRH input power could be controlled quite accurately). In the HI-scan the diamagnetic energy values were scaled to the same volume of 31.5m^3 using the volumes V_{Config} of the vacuum magnetic field, in the LI-scan - to the volume of 35m^3. Since for W7-X the dependence of the confinement on the density is not clear yet, three power dependences of the confinement time $\tau_E \sim n_e^\alpha$ are considered: a strong density dependence with α=0.54, corresponding to ISS04 scaling [6], a weak dependence with α=0.15, and a moderate dependence with a value in between, i.e. α=0.3.

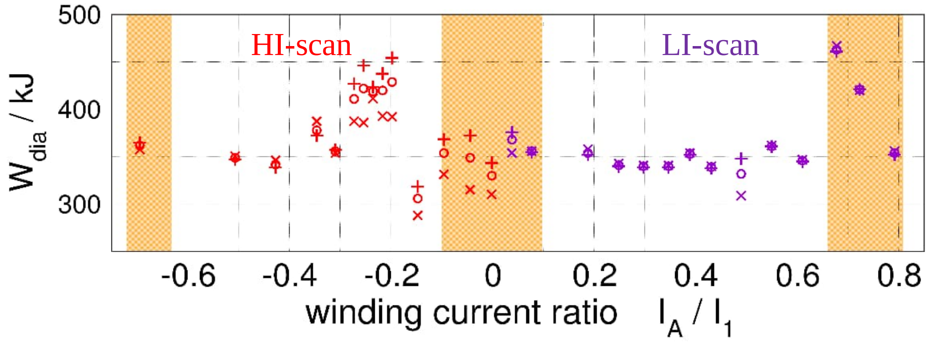

Fig. 3 Normalized Wdia – average, measured between 2.5 s and 2.9 s (for all shown here discharges), diamagnetic energy, which is scaled to a norm-volume of 31.5 m^3 in case of HI-scan and of 35 m^3 in case of LI-scan, as well as to a norm-line-density of $3.5 \cdot 10^{19}$ m^{-2}: $\langle Wdia \rangle \cdot (V_{norm}/V_{Config}) \cdot (3.5 \cdot 10^{19}/\langle n_{e,exp} \rangle)^\alpha$, α=0.15 (cross markers), 0.3 (circle markers), 0.54 (ISS04, plus markers).

In contrast to the HI-scan, the LI-scan does not show an obvious increase of plasma confinement in its intermediate limiter configurations (marked in white).

Like in OP1.2b observations, various diagnostics (e.g., segmented Rogowski coils, soft X-ray tomography system, correlation reflectometry) demonstrated crashing events (ILMs) in the intermediate configurations of HI-scan. The amplitude of ILMs correlates with the size of internal islands. LI-scan did not reveal similar observations, which might relate to the absence of 5/5-islands inside the LCMS. Fig. 4 shows first evaluations of the mode inversion radius in HI-scan from ECE-profiles for FMM002 configuration.

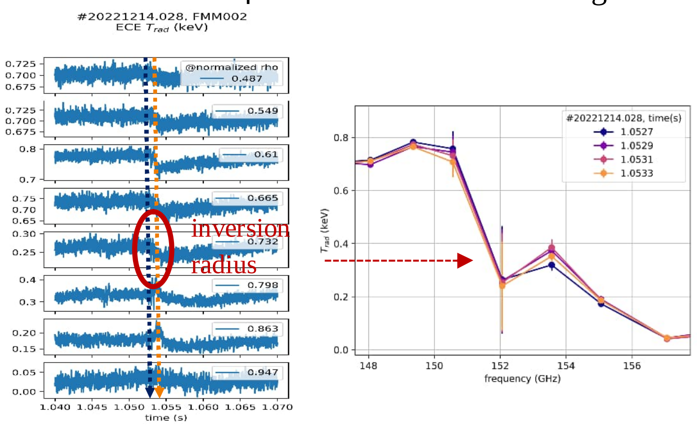

Fig. 4 ECE heat pulse studies: ILM indication and evaluation of the inversion radius (r_{eff_norm}=0.732).

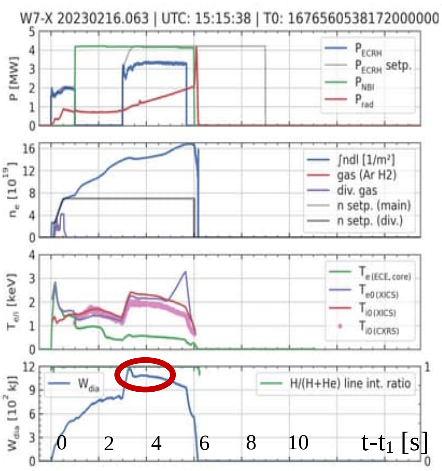

Fig. 5 High performance discharge in FMM002 configuration.

In the subset of HI-scan configurations, discharges with the record amount of the diamagnetic energy were demonstrated in FMM002 and FLM000 configurations. Fig. 5 shows the discharge with 1.2MJ diamagnetic energy, obtained with the combination 3.3 MW ECRH and 4 MW NBI heating. The high performance stage lasted more than 2 s. FLM000 configuration demonstrated 0.9 MJ diamagnetic energy with 4 MW ECRH heating only.

Summary

In the latest W7-X experimental campaign OP2.1 configuration scans were conducted exploring the magnetic configurations between the Standard and High iota as well as between the Standard and Low iota configurations. In each scan fruitful diagnostic data are obtained for 14 different configurations at similar experimental conditions allowing for further analysis of rotational transform dependencies.

The rotational transform variation confirmed an increase of the plasma energy and thus of the confinement time in the intermediate limiter configurations of HI-scan, revealed in OP1.2b experiments. First evaluations for LI-scan do not show similar observations.

ILMs were detected by various diagnostics in the intermediate limiter configurations of the HI-scan, confirming OP1.2b experimental results (in contrast to LI-scan). The profile analysis as well as SOL and turbulence studies are in progress based on the data obtained.

In the subset of the Standard - High iota magnetic configurations with improved confinement record values of the diamagnetic energy were achieved: 1.2 MJ with 3.3 MW ECRH combined with 4 MW NBI heating and 0.9 MJ with 4 MW ECRH heating only.

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

References:

[1] Grieger G. et al 1992 Fusion Technol. ***21*** *1767-1778*

[2] Andreeva T. et al 2022 Nucl. Fusion. ***62*** *026032*

[3] Wurden G. et al "Structure of island localized modes in Wendelstein 7-X." Proc. 46th EPS Conf. Plasma Physics (EPS-2019, Milan Italy) No. P2.1068

[4] Chaudhary, N., et al. "Radial localization of electron temperature pedestal and ELM-like events using ECE measurements at Wendelstein 7-X." 2023, https://doi.org/10.1051/epjconf/202327703004

[5] Andreeva T. et al 2017 Fusion Engineering and Design 123 129–132

[6] Yamada H. et al 2005 Nucl. Fusion 45 1684