Routes to high-performance operation in Wendelstein 7-X (W7-X): turbulence suppression with shaping of the density profile.

S.A. Bozhenkov[1], O. Ford[1], M. Wappl[1], S. Bannmann[1], T. Romba[1], V. Perseo[1], D. Zhang[1], K. Aleynikova[1], M. Ameer[3], I. Amri[1], J.P. Baehner[6], J. Baldzuhn[1], L. Baylor[4], Y. Boumendjel[1], C. Brandt[1], J. Brunner[1], C. Bueschel[1], D. Carralero[5], A. Dinklage[1], T. Estrada[5], G. Fuchert[1], Y. Gao[1], J. Geiger[1], T. Gonda[2], D. Gradic[1], K. Hammond[3], D. Hartmann[1], M. Hirsch[1], M. Jakubowski[1], J. Knauer[1], A. Knieps[9], M. Kriete[7], M. Krychowiak[1], A. Langenberg[1], H. Laqua[1], R. Lopez Cansino[8], J. Louwe[1], M. Maragkoudakis[5], P. McNeely[1], D. Moseev[1], D. Naujoks[1], N. Pablant[3], N. Panadero Alvarez[5], E. Pasch[1], P. Poloskei[1], J. Proll[1], K. Rahbarnia[1], F. Reimold[1], N. Rust[1], G. Schmidt[3], M. Siddiki, H. Smith[1], T. Stange[1], N. Tamura[1], H. Thomsen[1], A. Tsikouras[1], M. Vecsei[1], E. Villalobos Granados[1], A. von Stechow[1], J. Wagner[1], P. Xanthopoulos[1], M. Zanini[1], R. Wolf[1] and the W7-X team

[1]Max Planck Institute for Plasma Physics, Greifswald, Germany; [2]Auburn University, Physics, Auburn, USA; [3]Princeton University, Princeton Plasma Physics Laboratory, Princeton, USA; [4]Oak Ridge National Laboratory, Plasmaphysics, Oak Ridge, USA; [5]Centro de Investigationes- Medioambientales y Technologicas CIEMAT, National Fusion Laboratory, Madrid, Spain.; [6]MIT Plasma Science and Fusion Center, Cambridge, USA.; [7]Auburn University, Physics Department, Auburn, USA; [8]University of Sevilla, Spain; [9]Forschungszentrum Juelich GmbH, Institute of Fusion Energy and Nuclear Waste Management, Juelich, Germany

Introduction. Steep density gradients lead to improved plasma performance in the neoclassically optimized stellarator W7-X. This is evident in the global energy confinement time as well as in the ion temperature (T_i) and can be explained by a strong reduction of ITG turbulence *[Bozhenkov, NF 2020]*. Experimentally, such conditions can be achieved by several methods: dominant heating with neutral beam injection (NBI), injection of cryogenic hydrogen pellets and in some cases of low electron cyclotron resonance heating (ECRH) after fresh wall conditioning. The duration of the improved phase is usually determined by the ability to sustain the steep density gradient, by technical limitations of the involved systems and, eventually, may be limited by the plasma stability. In the last campaign, stable operational points could be determined experimentally and plasmas with improved performance could be extended for multiple seconds. In particular, the following combinations of the triple product (in the units of 10^{20} m^{-3} keV s) and duration could be achieved: 1.1 for 2 s; 0.83 for 4 s; 0.6 for 14 s; 0.5 for almost 25 s and the level between 0.3 and 0.4 for 40 s.

Database overview. In gas fueled plasmas with strong ECRH heating, the density profile is usually flat and the ion temperature is limited to about 1.6 keV, fig. 1 left. This finding is based on a wide experimental database of more than 2500 discharges, covering a wide range of densities and powers. There is a minor configuration effect: core T_i is lower by about 100 eV in the high mirror configuration and is higher by about 100 eV in the FMM configuration *[Andreeva, 3P216; Killer, O150]*. The clamping is broken with Ti reaching values of up to 3.2 keV with the same level of heating, if density peaking is created, fig.1 right. This is due to a major change in the energy transport. where turbulent heat fluxes become comparable with the neoclassical level *[Wappl, accepted to PPCF],* in contrast to plasmas without density peaking, where it exceeds the neoclassical level by a factor between 10 and 40. In addition, the characteristics of the impurity transport change dramatically with peaked densities. Impurity profiles are flat without the turbulence suppression, but change to highly peaked ones (impurity accumulation) for suppressed turbulence. The latter is consistent with the neoclassical expectations and shows a linear charge dependence *[Romba, O010]*.

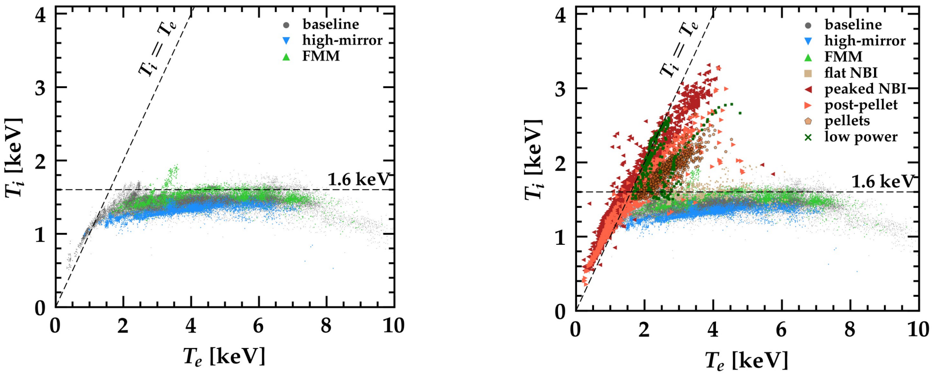


Figure 1. Left: T_i-clamping in plasmas with strong ECRH. Right – improved Ti with density peaking.

Theoretical explanation. Gyrokinetic theory predicts that the ion temperature gradient mode (ITG) is unstable and determines the transport under for plasmas with T_i-clamping. Moreover, recent simulations with a coupled framework of the gyrokinetic code GENE, neoclassical code KNOSOS and transport solver Tango can demonstrate quantitative agreement with the experimental profiles *[Banon Navarro, O006]*. It is concluded that the Ti-clamping is a result of dominant ITG turbulence, combined with a broad heating profile of the ions due to collisional heat exchange *[Beurskens, NF 2021]*. The ITG turbulence can be suppressed with density gradients. At the same time the trapped electron mode (TEM) turbulence is relatively weak in the W7-X geometry due to the separation of locations of trapped particles and regions of bad curvature *[Proll, PRL 2012]*. These two facts result in the formation of a stability valley *[Alcuson, PPCF 2020]* in linear simulations, which are further supported by nonlinear results *[Xanthopoulos, PRL 2020; Thienpondt, NF 2025]*. This explains the main experimental findings from the database analysis.

Scenarios. Experimentally, density peaking can be created in W7-X in four scenarios, which we briefly consider next: (i) injection of short pellet series; (ii) continuous pellet fueling; (iii) low power ECRH operation; and (iv) NBI plasmas with a balanced addition of ECRH.

Short pellet series. Injections of short, intense series of pellets result in strong density peaking. The ITG turbulence is suppressed after the pellet phase, the ion temperature rapidly raises above the clamping limit. The energy confinement time is improved above the ISS04 scaling *[Bozhenkov, NF 2020]*. The duration of the improved confinement depends strongly on heating power: for high powers, the improved phase is as short as 0.2 – 0.5 s, whereas for low heating powers the decay can take 2 - 4 seconds. The condition for the loss of the density gradient is identified with condition that a/L_T exceeds a/L_n. At the same time, the heat diffusivity remains at a low level until a/L_n drops below about 1.5. If the heating power is chosen low enough to keep a/L_T below a/L_n, the density gradient is preserved indefinitely and the shot cannot be distinguished from the low-ECRH case.

Low ECRH heating. A density gradient between r/a = 0.5 and 0.8 can be formed with edge fueling only, if the ECRH power is low (typically below 1 MW) and the plasma is shifted into regime with reduced energy and particle transport. The necessary condition for the development is a low edge density of about $0.1*10^{20}$ m^{-3}. Such plasmas can be maintained for long time: periods of up to 15 s were observed and were stopped at the pre-programmed end of the discharge. Typical core densities are about $0.5*10^{20}$ m^{-3}, T_i can be up to 2.4 keV and the confinement time is in the range 0.3 – 0.4 s. The density and temperature gradients are found to be similar (a/L_T is close to a/L_n) in the gradient

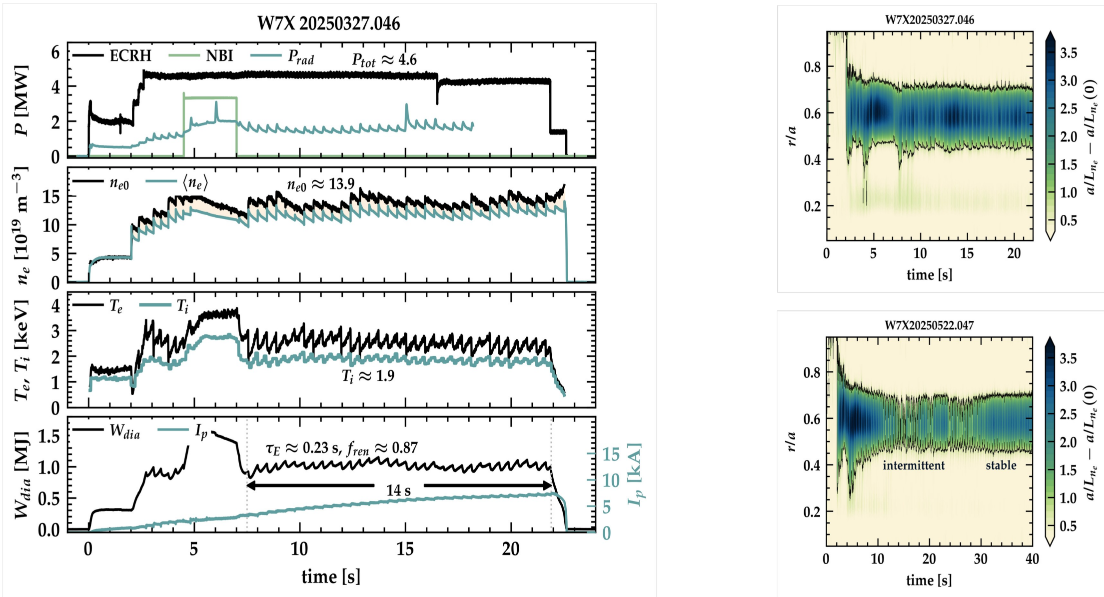
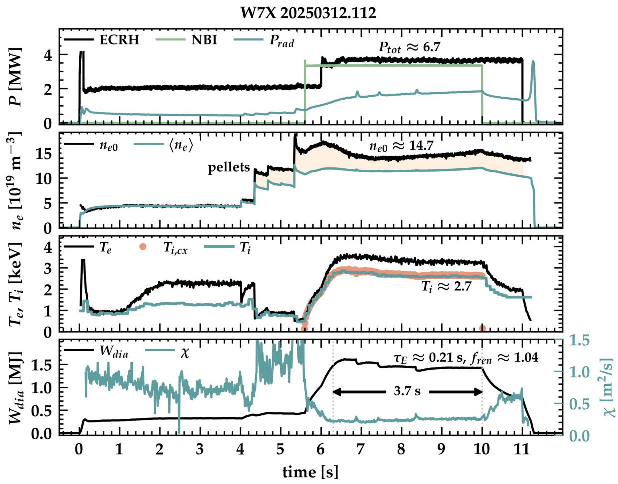


Figure 2. Left – time traces of plasma with density gradient maintained by continuous pellet fueling for 14 s. Right top – steady-state density gradient in the same shot. Right bottom – intermittent phases due to mismatch of the pellet parameters and of the used heating power.

zone in stable conditions. If a/L_T is raised too far by the additional heating, the density gradient and the improved confinement are lost. Scalability of this plasmas to higher core densities is unclear.

Continuous pellet fueling. In order to maintain a high core density with a density gradient, deep particle fueling appears essential. A new continuous pellet injector was recently installed at W7-X *[Meitner, 2020; Dinklage, 3P164]*. Figure 2 (left) demonstrates that continuous pellet fueling maintains stable plasma conditions and stable density gradients (right top) for 14 s. The plasma parameters given in the plot correspond to a triple product about 0.6. Such conditions were extended to about 25 s with a triple product above 0.5 and to 40 s with the triple product between 0.28 and 0.4. The reduction in the average triple product in the latter case results from the transient loss of the density gradient and transition to an intermittent phase (third plot in figure 2). This happens due to a transient mismatch between the pellet parameters and the heating level. Finer control of these ingredients will allow even longer plasmas at higher triple product value. We find that a/L_T exceeds a/L_n by about 20% at the gradient maximum in stable operation conditions (similar to discharge shown in fig. 2 left).

Combination of NBI and ECRH. It is found that sole NBI heating results in a strong density peaking at r/a between 0.4 and 0.6. These plasmas are characterized by reduced heat and particle transport *[Ford, NF 2024; Bannmann, NF 2024]*. With addition of the ECRH the gradient zone is narrowed, but the ion temperature can be increased to 3 keV. If the heating is raised too strongly, the gradient is lost and the plasma returns to the ITG dominated confinement. Thus, there is an optimum heating level that can be used for stable operation. An example of an experiment, where this condition was matched and good confinement was maintained for about 4 s, is shown in figure 3. The duration of the improved phase is limited by the NBI operating time. To maximize the use of NBI, the initial density peaking was created with pellets. The plasma parameters given in the figure correspond to a triple product of 0.83. If applied in a different configuration (limiter configuration FMM with compensated



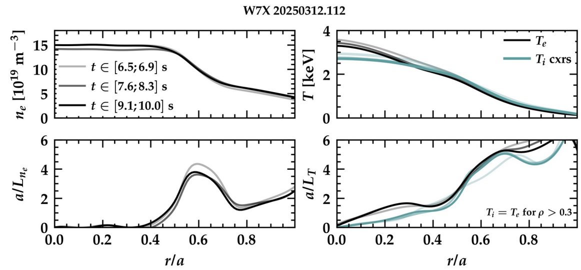


Figure 3. Left – time traces for the shot with high-Ti phase maintained for almost 4 s. Right – density and temperature profiles.

internal islands) with larger volume (r_{lcfs} of 0.55 m vs r_{lcfs} of 0.48 m) and different edge conditions, the same approach gives a triple product of 1.1. Since pellet fueling was not applied to create the initial gradient in this case, the duration of the improved phase is limited to 2 s, as the first 3 s of the NBI operation window were required for building up the density profile. In future this operation mode can be further extended in time to at least 10 s, if two NBI boxes are used successively. We find that the density profile can be maintained stable if a/L_T does not exceeds a/L_n by more than 20% at the gradient peak. We note that the impurity accumulation was not critical for the considered shots so far. The concentration of carbon, the main intrinsic impurity, remains at or below the level of about 1%. A better control of impurities may be required if these scenarios are further extended in time, especially when impurity seeding is used.

Summary. Density gradients lead to reduced heat transport and improved energy confinement. This is explained by the gyrokinetic theory by suppression of the ITG turbulence and generally weak TEM in the W7-X geometry. Experimentally, the gradients can be created with two main methods that can be scaled: continuous pellet fueling and NBI heating. Good confinement can be maintained for long periods with a proper choice of the ECRH heating in both cases: tens of seconds for the continuous pellet fueling and 4 seconds with the NBI heating. The condition for the stability of the density profile is the match between core particle sources and the reduced particle transport. If the heating is raised too strongly, the particle transport increases and the improved performance is lost or becomes transient. We find that the normalized temperature gradient should be kept at the level between 1 – 1.2 of the density gradient for the optimum stable operation. Control of this operational point with the use of real time density profile measurements, that are under development, and available heating and fueling actuators will allow even further extension of the improved confinement regime in time.