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The history of research into improved confinement regimes

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Abstract

Increasing the pressure by additional heating of magnetically confined plasmas had the consequence that turbulent processes became more violent and plasma confinement degraded. Since this experience from the early 1980ies, fusion research was dominated by the search for confinement regimes with improved confinement properties. It was a gratifying experience that toroidally confined plasmas are able to self-organise in such a way that turbulence partially diminishes resulting in a confinement with good prospects to reach the objectives of fusion R&D. The understanding of improved confinement regimes revolutionized the understanding of turbulent transport in high-temperature plasmas. In this paper the story of research into improved confinement regimes will be narrated starting with 1980.

1. Introduction

The release of energy from fusion processes between deuterons and tritons (DT-fusion) requires a high temperature to overcome the Coulomb potential wall, high density for frequent collisions and a high energy confinement time τ_E . For this purpose, fusion plasmas are confined by strong magnetic fields exerting the perpendicular Lorentz force. Plasma losses parallel to the magnetic field are avoided in toroidally closed magnetic geometry. The target parameters for the release of fusion power from a magnetically confined plasma [2] are known quite from the beginning of this endeavour and are specified in Lawson's famous criterion [3]. The critical parameter combination, which results from a power balance consideration, is the fusion triple product $n_i T_i \tau_E$, with n_i and T_i the ion density and temperature, respectively, and τ_E , the energy confinement time. The triple product governs the ratio of fusion power P_{fus} to lost power P_{loss} . For break-even⁴, $n_i T_i \tau_E \sim 8 \cdot 10^{20} \text{ m}^{-3} \text{ keV sec}$; for ignition, it is $\sim 4 \cdot 10^{21} \text{ m}^{-3} \text{ keV sec}$. This quality has not yet been achieved today but the toroidal systems, specifically the tokamak followed by the stellarator [2], are closest to it. Energy losses parallel to the magnetic field are avoided in toroidally closed confinement systems. The radial losses summing up to P_{loss} are predominantly caused by turbulent conduction and convection across nested flux surfaces from the plasma core where ideally the source is located to the plasma edge.

The triple product illustrates the important role of τ_E . It corresponds to the time, the plasma energy has to be replaced because of transport losses: $dE/dt = -E/\tau_E + P_{heating}$ (1). With a high confinement time, T_i at the maximum of the fusion reaction rate, about 20 keV, can be met with less heating power. Also the plasma density, for the reactor above 10^{20} m^{-3} , requires less external fuelling if the particle confinement time τ_p , defined in an equivalent form to equ. (1), is long. It is an empirical indication that the transport mechanisms inherent to toroidal systems are such that τ_p and τ_E are linked and generally

¹ This IPP report is an extended version with more detailed references of the paper: F. Wagner, "*The history of research into improved confinement regimes*" (2017) doi:10.1140/epjh/e2016-70064-9.

² Introductory textbook into fusion research: "*Fusion Physics*" - Vienna: International Atomic Energy Agency, 2012, edited by: Mitsuru Kikuchi, Karl Lackner, Minh Quang Tran; ISBN 978-92-0-130410-0.

³ J. D. Lawson, Proc. Phys. Soc. B70 (1957) 6.

⁴ break-even implies that the ratio Q of fusion power to external heating power to maintain this state is one.

vary together. Because of the importance of τ_E , there is a systematic effort in tokamak and stellarator research to improve energy confinement. The reactor requires a τ_E of a few seconds.

In the 80ies, the world-wide largest tokamak, JET of the EU programme, and the largest tokamak of the US fusion programme, TFTR, went into operation shortly followed by JT-60, the largest tokamak of the Japanese programme. An important innovative concept was to define the plasma surface by a null in the poloidal field and a magnetic separatrix allowing divertor operation for plasma exhaust [2]. With a separatrix, the material limiter, whose inner edge defines the toroidal plasma cross-section and whose presence gives rise to impurity release and plasma recycling can be avoided. The first poloidal field divertors with up-down X-points were PDX in PPPL Princeton, starting 1978 [5] and ASDEX in IPP Garching, starting in 1980 [6]. JT-60 started 1991 in a divertor configuration with the X-point in the midplane at the low-field side [7]. Divertor operation turned out to be so successful that even JET, originally conceived with limiter, was converted to a divertor in 1994 [8]. In the following period, only divertor tokamaks were conceived and ITER [9], the first experimental fusion reactor is, of course, a divertor tokamak. With respect to confinement, a very important quality of divertor devices was the low edge recycling of the working gas which allowed better control of the plasma density. The additional effort to install poloidal field coils to form an X-point allowed in many cases to shape the plasma cross-section and to improve the overall plasma stability. In such configurations, the dependence of τ_E on elongation ϵ and triangularity δ could be studied addressing the question to what extent improved stability leads also to better confinement. Also, in shaped configurations, plasma current I_p , safety factor q , internal inductance l_i and shear length L_s can be decoupled within limits.

Useful technologies were developed in this period for wall and limiter conditioning to provide low-recycling target plasmas for improved confinement states [10] and, somewhat later, wall coverage techniques with low-Z materials like boron [11] or lithium [12]. In divertors with low-Z wall layers, the role of atomic physics was strongly reduced and the intrinsic characteristics of high-temperature plasmas became more dominant and visible. Also, plasma operation became more reliable with reproducible discharges so that also the comparison of plasmas of different devices with different sizes became much more meaningful. The confinement analysis via multi-machine data bases yielded robust results for the dependencies on the so called engineering parameters (P_{heating} , I_p , electron density n_e , size....) or on dimensionless parameters like beta β , collisionality ν and reduced gyro-radius ρ^* ($= \rho/R$ ¹³).

Another, very important move at the beginning of the 80ies was the successful development and large-scale implementation of auxiliary heating systems. They supplemented and replaced ohmic heating and allowed plasma operation up to the respective limits. With auxiliary heating by energetic beams or

⁵ D. Meade et al., Proc. 8th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Brussels, 1980 (IAEA, Vienna 1981) Vol. 1, 665.

⁶ M. Keilhacker et al., Proc. 8th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Brussels, 1980 (IAEA, Vienna 1981) Vol. 1, 351.

⁷ JT-60 team, Plasma Phys. Control. Fusion 28 (1986) 185.

⁸ D. Stork et al., Proc. 15th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Seville, 1994 (IAEA, Vienna 1995) Vol. 1, 51.

⁹ "ITER Physics Basis", Nuclear Fusion 39 (1999) 2137ff and "Progress in the ITER Physics Basis", Nuclear Fusion 47 (2007) S1ff.

¹⁰ F. Dylla et al., Nuclear Fusion 27 (1987) 1221.

¹¹ J. Winter et al., Journal Nuclear Materials, 713 (1989) 162.

¹² J.L. Terry et al., Proc. 13th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Washington, DC, 1990 (IAEA, Vienna 1991) Vol. 1, 393.

¹³ R = major radius.

micro-waves in the gyro-frequency range of the ions or the electrons or at hybrid frequencies [2] the collinearity between heating power and plasma current (under OH conditions, $P_{OH} \sim I_p$) was broken up and the role of the electron temperature T_e – not any longer a hidden parameter - could explicitly be studied. This was very important because both collisional [14] and turbulent [15] transport processes depend sensitively on it.

With auxiliary heating, plasma confinement could be studied more realistically with parameters like β and density n closer to reactor conditions. Equally important was that high heating power, more than an order above the ohmic level, carried the plasmas to non-equilibrium states with unexpected properties. It was a gratifying experience that the self-organisation of plasmas under these circumstances carried the parameters closer to the ignition conditions and not unavoidably away from them. A wide variety of different confinement regimes appeared which widened the imagination of the fusion community – unfortunately not to the extent to create an appropriate terminology for them. The community was satisfied with names like B-mode, H-mode, I-mode, L-mode, P-mode, Z-mode...¹⁶.

The important advance for helical systems in the 80ies was also the availability of external heating. Up to then, because the technology was not available at high power, stellarators were heated ohmically. In this case, the unavoidable plasma current added internal rotational transform and changed the magnetic setting. Without ohmic current the confinement time improved in stellarators so that the authors could talk about “improvement of energy confinement” [17]. In this period, stellarators could stop concentrating essentially on basic feasibility issues but transitioned into a period where they contributed with relevant data at high β and low v . External heating, specifically electron cyclotron resonance heating (ECH), gave low core collisionalities putting the focus on the effects of the radial electric field on collisional (neo-classical) transport.

The parallel operation of different regimes, those with degraded or improved confinement, respectively, which differed strongly in collisionality, profile shapes, T_i/T_e - ratio... opened the door to comparative transport analysis linking transport features to the major regime characteristics. Transport theory could be applied to specific circumstances and adapted and refined in the comparison with experiment and its growing operational possibilities.

The subtleties of advanced operational modes with improved confinement characterized by steep gradients and fast transition times challenged the experimentalists to conceive novel diagnostics with unheard-of spatial and temporal resolutions. Without this development a better understanding of turbulent plasma transport would not have happened. Also dynamic techniques to measure plasma transport coefficients were developed using sawtooth heat pulses in tokamaks [18] or, pioneered by stellarators, modulation techniques of the heating power, e.g. using ECH [19]. These techniques allowed exploring the full 2x2 transport matrix including thermal forces constituting off-diagonal terms representing also core directed convective flows.

¹⁴ P. Helander and D. J. Sigmar, “*Collisional Transport in Magnetized Plasmas*” (Cambridge: Cambridge University Press, 2002).

¹⁵ A. Yoshizawa, S.-I. Itoh, K. Itoh “*Plasma and fluid turbulence; theory and modelling*”, Institute of Physics Publishing, Bristol and Philadelphia, 2002.

¹⁶ in alphabetic sequence.

¹⁷ WVII-A Team, NI-group, Proc. 9th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Baltimore, 1982 (IAEA, Vienna 1983) Vol. 2, 241.

¹⁸ J. D. Callen and G. L. Jahns, Phys. Rev. Letters 38 (1977) 971.

¹⁹ V. Erckmann et al., Nuclear Fusion 43 (2003) 131, and references therein.

These advancements are the reasons why I start narrating the history of research into improved confinement regimes in 1980.

2. Confinement and transport studies in the early 80ies²⁰

At the end of the 70ties, a major breakthrough in plasma confinement happened giving fusion research a good start into the 80ies. At PLT, the then leading tokamak in Princeton, high T_i values beyond 5 keV were achieved with neutral beam injecting (NBI). Though the plasma went deeply into the collisionless regime, good plasma confinement was maintained. These results demonstrated that the ion-temperature-gradient driven instabilities, so called ITG-modes [21], were not as deleterious as anticipated. When these results were reported at the IAEA conference 1978 in Washington, B. Kadomtsev, then the lead-theoretician from the other leading fusion institution, the Kurchatov institute in Moscow, congratulated after the presentation: “I congratulate you (R. Goldston) and the Princeton team on the very impressive achievement of reaching high ion temperatures and penetrating far into the collisionless region - a very important achievement for future reactor applications.”

Unfortunately, this good spirit did not last very long. Three urgently awaited and originally welcome advancements in tokamak operation led to disappointments regarding plasma confinement. Under ohmic conditions, the predominant technical situation in the 70ies, τ_E , governed by electron transport, increased linearly with density and, following the relation $\chi_e = a^2/4\tau_E$, the electron heat diffusivity χ_e decreased with density. This dependence, called Alcator scaling [22], was very favourable because the fusion triple product could have been expected to vary with density square.

Helical systems reported also a decrease of the electron heat diffusivity with density and additionally also with temperature: $\chi_e \sim 1/n_e T_e^{2/3}$ [23]. This even more optimistic scaling was obtained with ohmic heating where the electron temperature T_e is not an independent parameter. But the fits to the data could be improved including T_e in the scaling ansatz.

Better wall conditions, the first advancement, allowed all devices to expand their operation toward higher densities. The density scaling did not continue, however, and the Alcator scaling quality was lost. From a “knee-density” on, τ_E was found to stay constant with the tendency to even decrease approaching the density limit. Later, this branch of the ohmic τ_E scaling was dubbed “saturated ohmic confinement” (SOC) following the LOC (“linear ohmic confinement”) branch at low density. Transport analysis showed that the ion transport increased in the SOC regime beyond the neo-classical level and that ITG turbulence was the dominant culprit for confinement saturation [24].

The transition to auxiliary heating, the second advancement, caused τ_E to severely decrease from the ohmic reference level [25]. Plasmas entered the low-confinement L-mode which was stubbornly robust and reproducible independent of the heating method and its specific properties – being based on fast ions in parallel or perpendicular direction, or fast electrons or leaving largely thermal conditions.

²⁰ review papers on confinement are:

F. Wagner and U. Stroth, Plasma Phys. Control. Fusion 34 (1992) 1803.

B. A. Carreras, IEEE Transactions on Plasma Science, 25 (1997) 1281.

²¹ B. Coppi and F. Pegoraro, Nuclear Fusion 17 (1977) 969.

²² E. Apgar et al., Proc. 6th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden, 1976 (IAEA, Vienna 1977) Vol. 1, 247.

²³ D. V. Bartlett et al., Proc. 8th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Brussels, 1980 (IAEA, Vienna 1981) Vol. 1, 173.

²⁴ M. Wolfe et al., Nuclear Fusion 26 (1986) 329.

²⁵ D. W. Swain et al., Nuclear Fusion 21 (1981) 1409.

Again, enhanced ITG turbulence was made responsible for most of the L-mode confinement degradation. Though additional heating allowed increasing the plasma temperatures to levels not known up to then the triple product did not increase much because the confinement time degraded equivalently. In the discussion phase of the 11th IAEA conference, H. Rebut, then director of JET, was cited talking about a “lack of significance of auxiliary heating”²⁶. This gloomy situation became crystal clear to the participants of the 1984-EPS plasma physics conference in Aachen, when R. Goldston from Princeton, the same speaker who was applauded in 1978 for the high T_i -values in PLT, presented a multi-machine statistical analysis of the confinement behaviour with heating power P : τ_E degraded $\sim P^{0.5}$ [27]. The relevance of this finding is borne out by the frequency with which this paper has been quoted - 522 times²⁸. With this dependence – the so called “Goldston Catastrophe”²⁹ - as confinement basis increased technical challenges and economic restrictions would hardly allow the realisation of a tokamak reactor [30]. Besides power, the plasma current I_p became the leading scaling parameter of auxiliary heated tokamak plasmas: $\tau_E \sim I_p P^{0.5}$. Out of stability reasons it was not simply possible to offset the power degradation by increasing the current.

The helical systems were luckier with the transition from ohmic heating to external heating and simultaneously to net current-free operation – representing now the proper way of stellarator operation: a distinct improvement of confinement was observed [31].

The final surprise come when the new large tokamak devices allowed to compare their τ_E – values with those of the smaller ones leading to an unexpected size scaling with little or even no scaling with minor radius rather with an unexpected positive sensitivity on major radius R . Having in mind diffusive plasma transport, a scaling like $\tau_E \sim a^2 R$ was expected as it seems to apply for stellarators [32]. The strong R -dependence pointed toward the role of toroidicity in the form of trapped particles or magnetic shear S .

It was rather difficult to see how the fusion goal could be met with the confinement of degraded regimes. 10 years later, the situation had strongly changed so that Y. Miura from JAEA could start his talk at the 1990 IAEA conference in Washington with the statement: “Many kinds of improved discharges have been discovered in numerous tokamak experiments” [33] and R. Parker from MIT could present a long table of improved regimes in his summary talk of this conference [34].

At the beginning of the 80ies, a well-developed theory for collisional transport in toroidal geometry, the neo-classical transport theory, existed for tokamaks both for heat, particle and impurity transport [35] and for stellarators for heat and particle transport [36]. Collisional transport should dominate quiescent plasmas representing the lowest dissipation level. Transport characteristics parallel to the

²⁶ Contribution to the discussion by R. J. Taylor, Proc. 11th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Kyoto, 1986 (IAEA, Vienna 1987) Vol. 1, 110.

²⁷ R. J. Goldston, Plasma Phys. Control. Fusion 26 (1984) 87.

²⁸ Google search; Jan. 2017.

²⁹ M. Bell, PPPL Experimental Seminar, May 23, 2014.

³⁰ P.H. Rebut and P.P. Lallia, Fusion Eng. Design 11 (1988) 1.

³¹ WVIII-A TEAM, NI GROUP, Proc. 9th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Baltimore, 1982 (IAEA, Vienna 1983) Vol. 2, 241.

³² U. Stroth et al., Nuclear Fusion 36 (1996) 1063.

³³ Y. Miura et al., Proc. 13th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Washington DC, 1990 (IAEA, Vienna 1991) Vol. 1, 325.

³⁴ R. Parker, Proc. 13th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Washington DC, 1990 (IAEA, Vienna 1991) summary volume, 559.

³⁵ F. L. Hinton and R. C. Hazeltine, Review of Modern Physics 48 (1976) 239.

³⁶ A.A. Galeev and R.Z. Sagdeev, Review of Plasma Physics 7, (1979) 257.

magnetic field like plasma resistivity or bootstrap current are less affected by turbulence and determined by neo-classical transport. Ion heat conduction and Ware pinch [2] can be close to the neo-classical level in the plasma core or in specific corners of the operational domain; mostly, they are enhanced by plasma turbulence. Because of the spatial variation of the magnetic field in toroidal geometry, neo-classical viscosity determines parallel flows and the related radial electric field E_r . Later we will see how E_r , even at the neo-classical level, tames the plasma turbulence which has originally led to L-mode confinement.

Stellarators have unavoidably a 3-dimensional flux surface geometry. This fact alters strongly neo-classical transport because a further term adds to the magnetic field. In the tokamak, the field is modified by the toroidal inhomogeneity ε_t and is represented in the simplest form by $B = B_0 (1 - \varepsilon_t \cos\theta)$ whereas the stellarator field is represented by $B = B_0 (1 - \varepsilon_t \cos\theta - \varepsilon_H \sin(n\phi - m\theta))$ ³⁷. The helical inhomogeneity term ε_H causes locally trapped particles which drift out of the confining field and represent the major neo-classical loss channel. Unlike the tokamak, where the losses decrease with collisionality toward the long-mean-free path regime: $\Gamma \sim \nu$, they increase in helical systems: $\Gamma \sim 1/\nu$. In this case, scattering is beneficial because particles have a chance to leave the loss cone. Again, unlike the tokamak, the electron and ion fluxes are not intrinsically ambi-polar. The ambi-polar electric field E_r is determined from the charge balance $\Gamma_e = \Gamma_i$ in steady-state. E_r represents a thermal force and affects strongly the neo-classical transport coefficients. The neo-classical transport equations for stellarators are therefore non-linear allowing several roots – the electron root at low collisionality and the ion root at higher collisionality governing e.g. collisional transport at the edge [38]. Several roots can appear simultaneously, leading to bifurcations in the neo-classical fluxes. Because of its explicit role the radial electric field and bifurcating transport equilibria were in the focus of stellarator researchers much before these terms started to play a role in turbulent tokamak transport.

Plasma turbulence could be caused by electrostatic and magnetic instabilities driven to their saturated states by the constituents of the pressure or parallel current density gradient, the dynamics of trapped particles and by unfavourable magnetic curvature. One has to discriminate global magnetic instabilities like the $n=1, m=1$ mode in the plasma core which triggers periodic sawtooth relaxations and may even govern core transport from small-scale turbulence in the form of electrostatic drift-wave instabilities or magnetic micro-tearing, ballooning and rippling modes. In the plasma core turbulence is due to temperature gradient driven instabilities - the longer-wavelength ITG driven instabilities affecting in particular ion transport and the TEM (trapped electron mode) and the shorter wavelength, higher mode-number ETG (electron-temperature-gradient) instabilities which enhance predominantly electron transport. The ETG instability is seen as origin of the linear density scaling of τ_E in the LOC regime. The saturated stage of these instabilities establishes the turbulent transport level. Their dominant feature is that their transport rates steeply rise beyond a critical gradient [39]. The consequence of this threshold behaviour is that the relative temperature gradient is fixed close to the critical gradient with the corollary that temperature profiles are rather stiff (this feature was called “principle of profile consistency” [40]). These canonical profiles are shape-invariant to the location of the heat deposition profile. Under these conditions, the edge transport plays a significant role with a

³⁷ n and m describe the toroidal and poloidal periodicity.

³⁸ H.E. Mynick and W.N.G. Hitchon, Nuclear Fusion 23 (1983) 1053.

³⁹ J. W. Connor and H. R. Wilson, Plasma Phys. Nuclear Fusion 36 (1994) 719.

⁴⁰ B. Coppi, Comm. Plasma Phys. Control. Fusion 5 (1980) 261.

strong impact on global confinement. In case of stellarators canonical profiles for T_e and T_i are not typically observed [41].

There are operational ways to improve confinement as we have seen by increasing the density in stellarators or in ohmically heated tokamak plasmas, or the current in case of auxiliary heating but also by changing the configuration e.g. adding more triangularity δ . Confinement can also be improved by replacing hydrogen as working gas by a mix of hydrogen and deuterium or, better, by operating in pure deuterium [42] or even better by using exclusively tritium [43]. The primary objectives of this report are cases, however, where a new confinement regime is entered either induced from the outside or developing spontaneously as a bifurcation being the result of a process of self-organisation. An example for an induced transition is fuelling by the injection of frozen hydrogen pellets [2]. A particle source in the plasma core gives access to the class of confinement regimes with peaked density profiles. Edge fuelling by gas-puffing gives rise to the normally flat density profiles. The most prominent example of a spontaneous transition is the one from the low-confinement L- to the high-confinement H-mode whose “discovery and exploration” will be narrated below in some detail. L- and H-mode density profiles are both rather flat.

Stellarators were the first to notice a new class of confinement when the external heating technology was advanced enough to do without ohmic heating and plasma current [44]. The first results under proper stellarator conditions were published in 1980 by CLEO stellarator [45] using ECH and by W7-A under more relevant plasma conditions first with NBI [46] and later also with ECH [47] and by Heliotron-E in 1981 [48]. Initially, the improvement of confinement was attributed to the most obvious difference in the electron ensembles being a shifted Maxwellian in a tokamak. The improvement of confinement from the OH to the non-inductive phase was, for a short period, analysed in terms of the drift parameter $I_p/n_e T_e^{1/2}$ in agreement with the tokamak “Daughney scaling” [49]. But in 1986 Heliotron-E reported the confinement scaling $\tau_E \sim P^{-0.64}$ [50] acknowledging that the ubiquitous L-mode with its infamous scaling has spread also to stellarators. Henceforth, the sword of Damocles hovered over both representatives of toroidal confinement.

Not to get lost in the zoo of improved confinement regimes, we will first identify two classes and categorize them into the improved discharges with peaked or those with flat density profiles, respectively. This may be a bit artificial but it may reflect the situation of transport theory. In the middle of the 80ies theory was confronted with an interesting constellation: Anomalous transport could be improved either by realising extremely flat density profiles characteristic of the H-mode or peaked ones like in the “pellet (P)-mode”. The density inhomogeneity is the agent for all sorts of drift

⁴¹ F. Wagner et al., Phys. Rev. Letters 56 (1986) 2187.

⁴² M. Bessenroth-Weberpals et al., Nuclear Fusion 33 (1993) 1205.

⁴³ M.C Zarnstorff et al., Proc. 15th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Seville, 1994 (IAEA, Vienna 1995) Vol. 1, 183.

⁴⁴ H. Renner et al., IEEE Transactions on Plasmas Science, PS-9 (1981) 150.

⁴⁵ D. W. Atkinson et al., Proc. 8th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Brussels, 1980 (IAEA, Vienna 1981) Vol. 1, 153.

⁴⁶ W VII-A Team, Proc. 8th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Brussels, 1980 (IAEA, Vienna 1981) Vol. 1, 185.

⁴⁷ R. Wilhelm et al., Plasma Physics and Control. Fusion 26 (1984) 1433.

⁴⁸ A. Iiyoshi, Conf. on Alternate Fusion Concepts, Erice, Italy, March 23-27, 1981.

⁴⁹ C. Daughney, Nuclear Fusion 15 (1975) 967.

⁵⁰ K. Uo et al., Proc. 11th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Kyoto, 1986 (IAEA, Vienna 1987) Vol. 2, 355.

waves which were made responsible for turbulent transport. The two extremes – flat or peaked densities – seem to both tame them.

3. Improved confinement with peaked density profiles ⁵¹

3.1 Induced density profile peaking by central fuelling

In 1984, the Alcator C team was one of the first to report on confinement improvement by core particle fuelling via pellet injection [52]. The low density regime with the linear $\tau_E \sim n_e$ -scaling (LOC-regime) continued with gas-puffing being replaced by pellet injection toward higher density defining a third branch, the so-called P-mode with improved confinement compared to the standard saturated ohmic confinement regime (SOC-regime), the “ohmic L-mode”. The most obvious effect of core fuelling was the peaking of the density profile. This was the expected effect placing the particle source further in. But the essence of the P-mode turned out to be a change of particle transport initiated by central fuelling. The density profile showed gradients in the core without increase of the local particle source in cases where the particle source terminated halfway in. This situation in a source-free region can only stably be maintained when the diffusive losses, driven by the density gradient, are compensated by a convective inward flow of particles. The inward directed convection was first attributed to the neo-classical Ware pinch caused by the toroidal electric field in tokamaks. Transport analysis showed, however, that the Ware pinch was too weak to explain the core directed flow. The presence of an anomalous, turbulence driven inward pinch had to be concluded. The change in v_{in}/D with v_{in} being the turbulent inward velocity and D the diffusion coefficient are the cause for the profile peaking. The reduced convective losses are generally not sufficient to explain the τ_p improvement; a reduction of D had also to be conjectured.

The density peaking factor $n_{e0}/\langle n_e \rangle$ was the discriminator of the two confinement branches SOC and P-mode at otherwise identical or close to identical parameter settings. Modelling showed that the ion transport dropped from the enhanced level of the SOC-regime down to the neo-classical limit. Indeed, the density profile peaking moved $\eta=L_n/L_T$ below the expected critical threshold $\eta_{crit} \sim 1$ of the η_i -mode. The disappearance of the ion temperature gradient driven turbulence seemed to be the cause of the observed confinement improvement. An open question remained, however: What drives the turbulent inward term which starts the whole process? The ITG mode was stabilised but anyway, it was not suspected of driving strong particle fluxes.

In 1985, also Doublet III succeeded to improve the confinement with pellets using a centrifuge which allowed the injection of a string of pellets [53]. The broad density profile at the start peaked with core fuelling and broadened again when the particle source moved outward owing to the increased density. The ion temperature went up with the density profile peaking and in case of deuterium operation, the neutron flux increased by an order of magnitude. The observations were in line with ITG mode suppression. Apart from peaking of the density profile by external means it was operationally also necessary to reduce the edge density and to control recycling by the wall conditioning techniques which became popular at the time.

Core fuelling of ohmic and auxiliary heated plasmas became a standard technique on many tokamaks. On JET, regimes with improved confinement via density profile peaking by pellet injection were

⁵¹ F. Wagner and U. Stroth, Plasma Phys. Control. Fusion 34 (1992) 1803.

⁵² M. Greenwald et al., Phys. Rev. Letters 53 (1984) 352.

⁵³ S. Sengoku et al., Nuclear Fusion 24 (1985) 1475.

called PEP-mode, pellet-enhanced-performance mode [54]. The initial findings – reduction of ion transport, increase of core ion temperature correlated with a peaking of the density profile were unanimously confirmed also by helical systems. Pellet injection into beam heated Heliotron-E plasmas caused density and ion temperature profiles to peak, $T_i(0)$ went up by about 50% and τ_E increased by 30 - 40% [55].

3.2 Spontaneous density profile peaking with edge fuelling

The question - what governs particle transport - remained open and became more urgent because the peaking of the density profile was observed in cases where the particle source remained at the plasma edge. Already in 1979, two regimes with different density profile shapes were observed in Pulsator tokamak in hydrogen plasmas. The one with peaked profiles developed after the gas-puff had been instantly reduced. It showed lower ion transport at the neo-classical level [56] and impurities accumulated. In the case with broad n_e -profiles, the ion heat diffusivity was distinctively higher and no specific impurity effects appeared.

3.2.1 The Z-mode of ISX-B

The introduction of impurities e.g. neon injection into ISX-B plasmas led to a peaking of the electron density and ion temperature profiles and to an increase of confinement time by a factor of 1.8 above the standard level. This scenario, communicated in 1984 [57], could be realised in ohmic and beam heated plasmas. Besides the confinement improvement the linear scaling of τ_E with density was recovered. The Z-mode can be triggered from the outside but also develop if the plasma is sufficiently contaminated. Similar results were reported from T-10, the largest tokamak of the Russian fusion programme [58], developing a radiative confinement mode, called B-mode with peaked density profiles in comparison to its low-confinement counterpart, the S-mode [59] with broad ones.

3.2.2 The Supershot regime of TFTR and the hot-ion-mode

In 1986, the discovery of the so called Supershot regime was reported by TFTR [60]. Later, the Supershot was categorized as a hot-ion (high- T_i) mode as first developed by PLT with a strong non-thermal ion distribution in the core. The Supershot “pioneered by Jim Strachan based on experience in PLT”⁶¹ developed under strong core beam heating and low recycling edge conditions under balanced injection by minimising the transmission of a torque induced by off-balanced NBI into the plasma. Precondition of the Supershot regime was an extensive wall conditioning and outgassing of the graphite limiter [62] and preferentially the injection of lithium pellets into the low-density ohmic target plasma. With exclusively co- or counter NBI or with strong recycling at the limiter (e.g. by adding traces of He-gas which completely recycles) density peaking and confinement improvement did not occur.

Under low recycling conditions the edge density was kept low and density and temperature profiles showed a strong peaking with $n_e/\langle n_e \rangle$ up to 3.1 with the reward that τ_E increased above the corresponding L-mode level by up to a factor of ultimately 3.7. The strongest improvement in

⁵⁴ JET Team, Proc. 12th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Nice, 1988 (IAEA, Vienna 1989) Vol. 1, 215.

⁵⁵ K. Ida et al., Plasma Phys. Control. Fusion 38 (1996) 1433.

⁵⁶ F. Wagner, “*Ion energy balance in Pulsator*”, IPP Pulsator report III/52, Oct. 1979.

⁵⁷ E. A. Lazarus et al., Journal Nuclear Materials 121 (1984) 61.

⁵⁸ V. S. Strelkov, Plasma Physics Reports 27 (2001) 819; translated from Fizika Plazmy, Vol. 27 (2001) 867.

⁵⁹ Yu. V. Esipchuk et al., Plasma Phys. Control. Fusion 28 (1986) 1253.

⁶⁰ J. D. Strachan et al., Phys. Rev. Letters 58 (1987) 1004.

⁶¹ M. Bell, PPPL Colloquium November 18, 2014.

⁶² F. Dylla et al., Nuclear Fusion 27 (1987) 1221.

transport happened in the ion channel. Core ion temperatures of up to 38 keV were achieved. The DT programme of TFTR was carried out in the Supershot regime and thanks to the high core parameters a fusion power of 6.2 MW could be achieved with 29.5 MW external heating [63]. Destroying the low recycling conditions with a He-puff caused T_i to collapse down to $\frac{1}{4}$ of its original value [64].

The transport analysis of Supershot plasmas identified by a drop of the ion transport by a factor of 10 down to the neo-classical level needed, however, a much more sophisticated approach than simply using the η_i -criterion. This topic will be continued in chapt. (5).

Hot-ion modes were realised later in many other devices and regimes also under L- or H-mode conditions. A high- T_i mode was also developed in Heliotron-E in 1995 with strong beam heating and low wall recycling [65]. The core ion temperature doubled and the confinement time increased by 30-40%.

3.2.3 The IOC regime of ASDEX⁶⁶ and the “re-heat” mode of CHS

The regime of improved ohmic confinement (IOC) of ASDEX developed in 1988 by strongly lowering the edge density via a sudden reduction of the gas puff rate [67]. The density profile peaked from neo/ $\langle n_e \rangle \sim 1.4$ to ~ 2.2 . The reduction of the gas input seemed to be the pre-requisite to access this state; the instantly improved particle confinement maintained the particle content at a reduced fuelling rate. With the density, also the ion temperature profile peaked but to a lesser extent so that η_i dropped. The T_e profile remained unaffected and sawteeth continued in the core. τ_E followed the linear LOC density scaling establishing the IOC confinement branch with τ_E values superior to those of the SOC regime at identical line density. As seen above, the IOC branch could also be accessed by core fuelling with pellets. Formally, the IOC confinement continued the Alcator scaling of the LOC regime. The conditions have changed, however. Whereas electron transport governed the LOC regime with flat density profiles, strongly peaked ones formed under IOC conditions with the ion transport being close to or at the neo-classical level.

Unlike the Supershot regime with strong beam fuelling or pellet refuelled discharges, the density profile peaking in the IOC regime develops though the particle source remained at the edge. As it is based on an improvement of particle confinement it could only be realised in ASDEX with deuterium but not in hydrogen plasmas. The isotopic effect applies also to particle confinement with hydrogen requiring a higher fuelling rate from the outside under ohmic conditions and displaying n_e -profiles even broader than those with deuterium. Only in deuterium the trick with reduced puff rate worked causing a rapid drop in edge density and a peaking of the density profile.

In 1990 at the IAEA conference in Washington, JIPP T-IIU reported on the realisation of the IOC regime [68]; in 1999, TEXTOR achieved it in ohmic limiter discharges when the gas valve was closed

⁶³ J.D. Strachan et al., Phys. Rev. Letters 72, 3526 (1994).

⁶⁴ E.R. Ernst et al., in Proc. 17th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Yokohama, 1998 (IAEA, Vienna 1999) paper Vol 2, 741.

⁶⁵ K. Ida et al., Plasma Phys. Control. Fusion 38 (1996) 1433.

⁶⁶ Review on regimes with peaked density profiles in ASDEX: K. Lackner et al., Plasma Physics and Control. Fusion 31 (1989) 1629.

⁶⁷ F.X. Söldner et al., Phys. Rev. Letters 61 (1988) 1105.

⁶⁸ K. Toi et al., Proc. 13th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Washington DC, 1990 (IAEA, Vienna 1991) Vol. 2, 301.

[69]. The confinement time grew from the SOC level of 105 ms to 140 ms of the IOC branch. EAST established the IOC regime in 2011[70].

In CHS, the termination of the external gas puff led also to a peaking of the density profile typically from $n_{e0}/\langle n_e \rangle \sim 1$ to ~ 2 and a concomitant improvement in the energy content at constant beam power. This behaviour, observed also in other helical systems, was called “reheat phenomenon” [71]. The confinement improvement also occurred in the density range where τ_E saturated following the linear variation at lower density.

3.2.4 Counter neutral beam injection into ASDEX plasmas ⁷²

Neutral beam injection parallel to the plasma current (co-NBI) of ASDEX led to the L-mode when the power remained below the H-mode threshold. Counter neutral beam injection (ctr-NBI) opposite to the plasma current has a broader deposition profiles and potentially higher orbit losses but gives rise to a more negative electric field. Ctr-NBI into ASDEX plasmas has led to a different confinement regime in the L-mode power range characterised by peaked density and ion temperature profiles. The ctr-NBI regime was observed the first time in ASDEX in 1988 [73]. Like in other cases with peaked profiles a pre-requisite for the formation of this regime was the reduction of external gas puffing. With this initiation, the density profile gradually peaked from the typical L-mode level of $n_{e0}/\langle n_e \rangle \sim 1.4$ to ~ 2.4 . This process went on for several L-mode confinement times and τ_E improved along with the n_e profile peaking. The confinement improvement seemed to follow the peaking. After a sawtooth the n_e -profile transiently flattened and τ_E dropped. The energy content recovered thereafter at a rate which corresponded to the heating power. Like in the other cases with peaked density profiles transport analysis indicated that ITG turbulence was low because η_i -modes were stabilised by peaked n_e -profiles and the ion heat transport was found to be at the neo-classical level [74].

The ASDEX results have been reproduced by JFT-2M, the JAERI tokamak, in 1992 confirming the striking difference in density profile shape between co- and ctr-NBI. The energy confinement improved by about 30%. DIII-D reported in 1996 a reduction of the turbulence level with ctr-NBI compared to co-injection. But the ctr-NBI regime had no wider resonance in the community possibly because impurities accumulated strongly. As the impurity result was not unexpected and in agreement with collisional transport theory [75] no specific potential was seen in it. However, in 2002 ctr-NBI was picked up again by DIII-D and led to the improved QH-mode regime (see chapt. 4.3.4).

3.2.5. The RI-mode of TEXTOR

In 1994 the TEXTOR team reported on the development of the “radiative improved (RI)-mode” which recovered the LOC density scaling but with auxiliary heating [76]. The RI-mode could be accessed by puffing small amounts of neon into the limiter discharge or unintentionally by Si erosion from freshly siliconized plasma walls. In this case, the RI mode developed from the beginning on. The most obvious feature of the RI-mode is the peaking of the density profile. The profile peaking reflected the

⁶⁹ R.R. Weynants et al., Nuclear Fusion 39 (1999) 1637.

⁷⁰ Y. Yang et al., Plasma Science and Technology 13 (2011) 312.

⁷¹ S. Morita et al., in Proc. 14th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Würzburg, 1992 (IAEA, Vienna 1993) Vol. 2, 515

⁷² Review on regimes with peaked density profiles in ASDEX: K. Lackner et al., Plasma Physics and Control. Fusion 31 (1989) 1629.

⁷³ O. Gehre et al., Phys. Rev. Letters 60 (1988) 1502.

⁷⁴ V. Mertens et al., Plasma Phys. Control. Fusion 32 (1990) 965.

⁷⁵ G. Fussmann et al., in Proc. 12th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Nice, 1988 (IAEA, Vienna 1989) Vol. 1, 145.

⁷⁶ A.M. Messian et al., Nuclear Fusion 34 (1994) 825.

improved particle confinement owing to a stronger inward pinch. The confinement time reached values comparable to those of the H-mode (see below) and even above those close to stability limits like the Greenwald density limit [77]. Transport analysis showed that the reduction of the ion transport must be the major cause of the improved confinement. ITG turbulence was expected to be fully suppressed whereas the increased Z_{eff} by impurity puffing was found to be instrumental to reduce the ITG growth rate. Because of the similarity in major characteristics and transport properties, the authors of [78] spoke about the “LOC-IOC-RI mode regime”. The RI-mode could be reproduced by DIII-D [79] stressing the role of $E \times B$ shear stabilisation of turbulence at reduced growth rate owing to the presence of impurities.

4. Improved edge confinement with broad density profiles

4.1 The H-mode of ASDEX⁸⁰

The “high confinement” H-mode was discovered in ASDEX in February 1982 during neutral beam heating [81]. The H-mode turned out to be a robust and ubiquitous confinement regime allowing later with JET the highest Q-values attained so far. The beam phase of ASDEX discharge # 4734 – the first H-mode - started as usual with an L-phase, the low-confinement counterpart, with degraded particle and energy confinement. This period could last for several L-mode confinement times and represented a state of transport equilibrium. Suddenly at constant power and without interference from the outside the plasma could jump into a new regime with improved particle and energy confinement. The time for transition was much shorter than the energy confinement time and could be as short as $\sim 100 \mu\text{s}$. This discrepancy in time scales pointed toward a bifurcating process. The improvement of the confinement time restored on one hand the hope to finally meet the fusion mission and the distinct transition offered on the other hand an excellent opportunity to possibly unravel the physics behind turbulent transport. These two objectives governed much of the fusion R&D in the following decades and nearly 35 years after the H-mode discovery the hopes were somewhat fulfilled: ITER, being based on the H-mode confinement quality, has been approved and is being built and the understanding of plasma turbulence is much more advanced along a line which is not solitary to plasmas but rather ubiquitous to strongly driven thermodynamically open systems. Review papers on H-mode and H-mode physics are [82, 83]; a summary of the H-mode status 25 years after its discovery is given in [84].

On ASDEX, the first H-mode was observed in the upper single-null divertor configuration. Double-null and lower single-null configurations could not be operated at the time because a toroidally closed belt limiter was installed at the plasma vessel bottom closing the lower divertor. The purpose of this installation was to clarify some of the obvious exhaust and plasma-wall-interaction advantages of the divertor compared to the limiter but now under near equal power loading conditions [85]. 1982 was

⁷⁷ M. Greenwald et al., Nuclear Fusion 28 (1988) 2199.

⁷⁸ R. Weynants et al., Nuclear Fusion 39 (1999) 1637.

⁷⁹ T. S. Taylor et al., in Proc. 17th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Yokohama, 1998 (IAEA, Vienna 1999) Vol. 1, 49.

⁸⁰ Review: ASDEX team, Nuclear Fusion 29 (1989) 1959; written on the basis of the IPP internal report F. Wagner “*Confinement studies on ASDEX*”, IPP III/131, Feb. 1988.

⁸¹ F. Wagner et al., Phys. Rev. Letters 49 (1982) 1408.

⁸² ASDEX-team, Nuclear Fusion 89 (1989) 1959.

⁸³ K. H. Burrell et al., Plasma Phys. Control. Fusion 34 (1992) 1859.
K. H. Burrell, Phys. Plasmas 4 (1997) 1499.

⁸⁴ F. Wagner, Plasma Phys. Control. Fusion 49 (2007) B1.

⁸⁵ H. Vernickel et al., Jour. Nucl. Materials, Volumes 111–112 (1982) 317.

still the period where the divertor concept was pioneered under the eyes of the (partially) sceptical limiter community. It was a blessing that the belt limiter enforced upper single-null operation at a fortuitous counter-clock-wise B-field direction, which caused the ions to drift toward the X-point. Later, when the limiter was removed again, it turned out that single-null operation and ion-gradB drift direction were essential to get into the H-mode at the level of the then available power. More about this, later.

The sudden transition into the H-mode could not be missed because it affected basically all diagnostics on ASDEX at the time: The signal of the D_α detectors monitoring the divertor or the main plasma dropped instantly at the transition. This became the dominant regime monitor. Simultaneously, the density increased in all interferometer channels. The two together clearly showed that the particle confinement improved. In the L-mode just the opposite happened: Despite of beam fuelling and increased ionisation rate, the plasma particle content decreased. Diamagnetic and equilibrium β increased by an increment which was typically twice the one of the L-mode. Despite of the density increase, also the electron temperature increased and the loop voltage dropped. At the transition, the magnetic turbulence level dropped providing the first hint that the improved confinement might be caused by a reduction of turbulent transport. The more quiescent nature of the H-mode was also borne out by the lower noise level on the D_α traces after the transition. Figure 1 is taken from the first publication on the H-mode [86]. The densities are compared of an L-mode (#4803) and the consecutive H-mode (#4804) discharge reflecting the bifurcation in particle confinement.

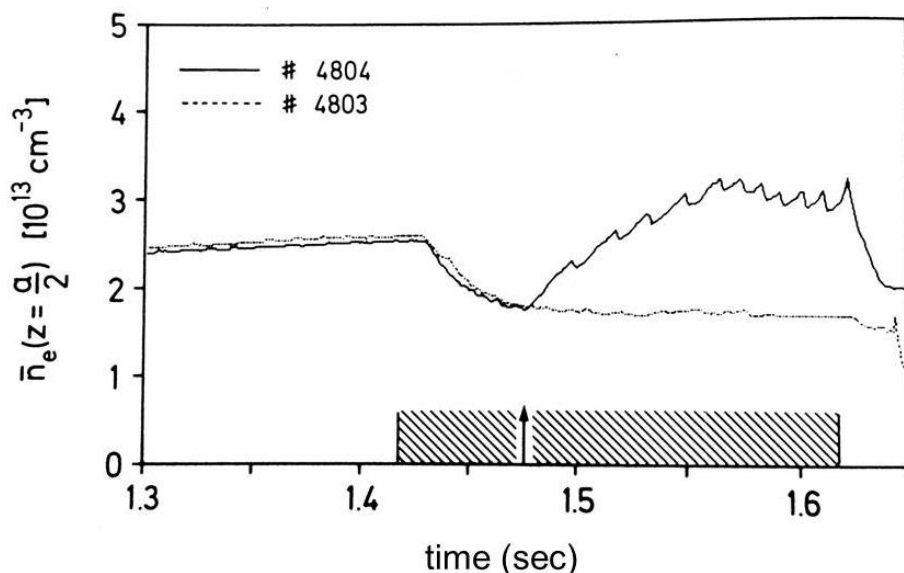


Figure 1. Density variation during neutral beam injection for an L- and H-mode plasma of ASDEX. The viewing line of the interferometer impacts at $r = a/2$.

A critical condition had to be met for the H-transition manifested by a power threshold well above the ohmic power level of ASDEX with its circular cross-section. This critical condition could be met with deuterium target plasmas and deuterium or hydrogen injection but not with hydrogen injection into hydrogen plasmas. The mysterious isotope effect of confinement [87], which introduces an alien element into an environment governed by gyro-Bohm transport scaling, gained new weight by the

⁸⁶ F. Wagner et al., „Variation of the particle confinement during neutral injection into ASDEX divertor plasmas“, IPP III/78, June 1982.

⁸⁷ M. Bessenroth-Weberpals et al., Nuclear Fusion 33 (1993) 1205.

mass-scaling of the H-mode power threshold⁸⁸. The inherently non-linear relation between energy content and heating power, which is the essence of this self-organised process, manifested itself by a cyclic process. The H-mode started with a dwell time on the low L-mode branch prior to the transition. The dwell time to the H-mode could be reduced in low-q operation. Larger sawteeth at an extended $q=1$ radius were able to enforce an H-mode transition. After the jump onto the H-mode branch the plasma moved deeper into this regime. When the beam power was finally switched off the plasma stayed in the H-phase again for a dwell time before it jumped back onto the L-mode branch where it started from. Generally, a hysteresis is observed in this cyclic process in the sense that the power threshold P_{thr} is higher than the power across the separatrix at the H-L back transition. The hysteresis aspect concerns the nature of the bifurcation [89], the details depend, however, on the ion-grad-B drift direction, the external gas fuelling and on many aspects which are not yet completely sorted out. A natural asymmetry of the two subsequent transitions is that the L-H transition starts at L-mode transport and edge gradients whereas the back transition starts with H-mode transport and steep edge gradients. This aspect may cause the hysteresis in P_{thr} of about a factor of two. Later, edge measurements showed nearly no difference in local temperature for the two transition time points [90].

With the power threshold, the sawtooth trigger and the dwell times it was clear that either the electron or the ion temperature must play a decisive role for the H-transition. They are the parameters, primarily affected by the heating power or by the thermal wave of a sawtooth. Maybe, because the edge electron temperature could be measured more easily and reliably than the edge ion temperature, many observations were made which supported T_e as parameter crucial for the transition. This was the view on ASDEX and the evidence is collected in [91]. The successor of ASDEX⁹², ASDEX Upgrade, could not confirm this conjecture. Decades later, F. Ryter and co-authors stressed already in the abstract of their paper “Survey of the H-mode power threshold and transitions physics studies in ASDEX Upgrade”[93]: “Dedicated L-H transition studies... reveal that the ion heat flux is a key parameter in the L-H transition physics mechanism... The electron channel does not play any role.” Paradigm changes like this are the essence of progress in science. In ECH heated W7-AS plasmas H-mode transitions needed an increase in density with rising power obviously to couple the ions onto the heated electrons as conjectured in [94]. This is the generally accepted view now.

The sawtooth which triggered the H-mode was often the last one to appear and the plasma core was quiet during the H-phase. However, a new relaxation appeared at the edge. Edge Localised Modes (ELMs) [95] appeared right after the transition causing periodic losses and limiting the pressure gradient at the plasma edge. Now we know that, as a consequence of the confinement improvement, the edge gradients are not limited by transport rather by stability. The narrow edge zone with steep

⁸⁸ recent results from ASDEX Upgrade show that the difference in P_{thr} is due to the higher ion heat flux in hydrogen. F. Ryter et al., Plasma Phys. Control. Fusion 58 (2016) 014007.

⁸⁹ K. Itoh, Plasma Phys. Control. Fusion 36 (1994) A307.

⁹⁰ F. Ryter et al., Plasma Phys. Control. Fusion 40 (1998) 725.

⁹¹ ASDEX-team, Nuclear Fusion 89 (1989) 1959; written on the basis of the IPP internal report F. Wagner “*Confinement studies on ASDEX*”, IPP III/131, Feb. 1988.

⁹² ASDEX stopped operation in summer 1991. The machine was dismantled by engineers and technicians from the South Western Institute of Physics (SWIP), transported to Chengdu, China, and newly set-up there in a brand-new building and operated since 2002 as HL-2A. This device is in use up to now and it has contributed and still contributes with many interesting results also to the understanding of the H-mode physics.

⁹³ F. Ryter et al., Nuclear Fusion 53 (2013) 113003.

⁹⁴ F. Wagner et al., in Proc. 15th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Seville, 1994 (IAEA, Vienna 1995) Vol. 1, 559.

⁹⁵ M. Keilhacker et al., Plasma Phys. Control. Fusion 26 (1984) 49.

pressure gradients and high current density (mostly bootstrap current) is repetitively affected whenever critical parameters hit the peeling-ballooning limit [96]. This relaxation process introduces a quasi-steady-state situation. The efforts to avoid ELMs in ASDEX were not paid off. It was possible to suppress ELMs by carefully positioning the plasma inside the vessel and the energy confinement time benefitted from this endeavour. But so did also the impurity confinement time. Without ELMs, the good particle confinement caused the impurity radiation to quickly increase. Quiescent H-modes were never steady-state in ASDEX. The large power fluxes during the ELMs are still a severe concern and a drawback of the H-mode. Since its discovery there has been a strong effort to explore ways to avoid ELMs without losing the good confinement (see chapt. 4.3).

The H-mode and its characteristics as they could be identified with the limited diagnostic capabilities at the time were first presented to an international community at the 3rd Joint Grenoble–Varenna International Symposium, March 1982 [97] and then in the Baltimore IAEA conference in fall 1982 [98]. Outside the official agenda of this conference a special evening session was organised by P. Rutherford where the author of this paper was cross-questioned by an audience which fulfilled the ground rule of science - to be sceptical. Thereafter, the H-mode was accepted as a new object in plasma physics. Some of the initial results from ASDEX were originally published as an internal IPP report [99] which formed the basis of the final Phys. Rev. Letters paper which appeared in fall 1982 [100]. The major issues after publication of the initial findings were – how to realise the H-mode in other devices, - what is the trigger for the H-mode transition, and which mechanism tames the turbulence in the H-phase.

The first issue was quickly solved: PDX [101] reported the H-mode in 1984; prerequisites were operation with a separatrix and a more tightly closed divertor to locally concentrate recycling. Doublet III followed shortly thereafter [102] confirming the need to operate in deuterium. Like ASDEX, no obvious power degradation of confinement in the H-mode was observed. In 1985 [103], JET demonstrated that the H-mode could also be realised in the worldwide largest tokamak. Then, JET was still a limiter device which could, however, be operated with an X-point inside the vessel but close to the wall thanks to its shaping coils. The late A. Tanga was the motor behind these studies. With the H-mode, the confinement time doubled. JET benefitted from the H-mode because later, when it operated in DT, the highest Q of 0.65 was attained in this regime [104]. Q short of 1 was expected for JET when the project was approved whereat its objectives were defined on the scientific basis of the 70ies, plasmas were still ohmically heated and the Alcator confinement scaling was the only reference. The JET goal was finally met, however along a totally different confinement route and physics basis.

⁹⁶ J. W. Connor et al., Phys. Plasmas 5 (1998) 2687.

⁹⁷ F. Wagner et al., “First results from neutral beam heating of diverted ASDEX discharges”, Proceedings of the 3rd Joint Grenoble–Varenna International Symposium, Centre d'Etudes Nucleaires de Grenoble–France, 22–26 March 1982, Pages 35-48.

⁹⁸ F. Wagner et al., in Proc. 9th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Baltimore, 1982 (IAEA, Vienna 1983) Vol. 1, 43.

⁹⁹ F. Wagner et al. „*Variation of the particle confinement during neutral injection into ASDEX divertor plasmas*“, IPP III/78, June 1982.

¹⁰⁰ F. Wagner et al., Phys. Rev. Letters 49 (1982) 1408.

¹⁰¹ S. M. Kaye et al., Jour. Nuclear Materials 121 (1984) 115.

¹⁰² M. Nagami et al., Nuclear Fusion 24 (1984) 183.

¹⁰³ A. Tanga et al., in Proc. 11th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Kyoto, 1986 (IAEA, Vienna 1987) Vol. 1, 65.

¹⁰⁴ M. Keilhacker et al., Nuclear Fusion 41 (2001) 1925.

In 1987, JFT-2M, the JAERI tokamak, discovered the H-mode also in the limiter configuration needing, however, twice the expected heating power (ICH) [105] confirming the initial ASDEX ICH results from 1987 [106]. In all these devices the transition was spontaneous. In 1991, TUMAN, the tokamak of the IOFFE Institute in St. Petersburg, induced the H-mode by a strong gas puff applied to the plasma edge [107].

Spherical tokamaks (STs) with low aspect ratio A promise easier access to the H-mode because the higher field curvature improves ITG stability. However, the actual values for the power threshold are higher. Nevertheless, all major STs can work in the H-mode. Already the pioneering device of this tokamak variant, START of CCFE in Culham, showed H-mode transitions [108]. MAST, the large successor of START reported on the H-mode in 2001 [109], NSTX the spherical tokamak of PPPL followed in 2002 [110] and Globus-M, the one of the IOFFE Institute in St. Petersburg, in 2007 [111]. These H-modes showed all secondary characteristics known from conventional aspect-ratio tokamaks including ELMs. Also in STs gas puffing and recycling plays a crucial role to access the H-mode. Gas puffing from the low-field side could quench the H-mode, and could initiate it from the high-field side. H-mode research in spherical tokamaks benefitted from the rather open geometry of these devices allowing good diagnostics access.

With the H-mode accessible at low edge collisionality at JET and high edge collisionality in JFT-2M, under divertor or limiter conditions, it was clear that every tokamak would be able to realise it provided that certain conditions were fulfilled: The beam power has to be above a threshold which is higher in limiter configuration and in hydrogen, lower at low magnetic field and, as we have seen in case of ASDEX, with single null operation and the ion-gradB drift directed toward the X-point. Gas-puffing from the high-field side or the divertor or lower- q operation with large sawteeth as H-mode trigger assisted the transition. In 1992 the H-mode was realised in W7-AS stellarator with boronised walls [112] following the above mentioned recipe and in CHS heliotron with NBI. This progress was reported at the 1992 IAEA meeting in Würzburg [113]. The H-mode was achieved in W7-AS both with electron cyclotron heating (ECH) and NBI at $i \sim 0.5$ when the configuration was limited by a separatrix and the poloidal viscosity by magnetic pumping was low. The W7-AS H-mode showed all the features of tokamak H-modes including ELMs [114]. The power threshold turned out to be rather low but operationally, the density had to be matched to the heating power. The H-mode was realised in 2004 in LHD at low field [115], and in the same year and – of specific importance for the future

¹⁰⁵ H. Matsumoto et al., Nuclear Fusion, 27 (1987) 1181; paper submitted Oct. 20., 1986

¹⁰⁶ K. Steinmetz et al. Phys. Rev. Letters 58 (1987) 124; paper submitted Sept. 4., 1986

¹⁰⁷ S. G. Askinazi et al., in Proc. 13th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Washington DC, 1990 (IAEA, Vienna 1991) Vol. 1, 509.

¹⁰⁸ D. A. Gates et al., Phys. Plasmas 5 (1998) 1775.

A. Sykes et al., Phys. Rev. Letters 84 (2000) 495.

¹⁰⁹ A. Sykes et al., Phys. Plasmas 8 (2001) 2101.

¹¹⁰ R. Maingi et al., Phys. Rev. Letters. 88 (2002) 035003.

C. E. Bush et al., Proc. of 29th Euro. Conf. on Plasma Phys. and Contr. Fusion, Montreux, June 17-22, 2002.

¹¹¹ V. K. Gusev et al., 34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.31F, P-1.078 (2007).

¹¹² V. Erckmann et al., Phys. Rev. Letters 70 (1993) 2086 .

¹¹³ V. Erckmann et al., in Proc. 14th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Würzburg, 1992 (IAEA, Vienna 1993) Vol. 2, 469.

K. Toi et al., in Proc. 14th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Würzburg, 1992 (IAEA, Vienna 1993) Vol. 2, 461.

¹¹⁴ F. Wagner, Plasma Phys. Control. Fusion 49 (2007) B1.

¹¹⁵ K.Toi et al., Nuclear Fusion 44 (2004) 217.

stellarator programme - in the optimised and quasi-symmetric device, He-J [116]. The TJ-II heliac followed in 2010 with NBI and Li-coated walls [117]. In an induced fashion using biasing probes H-1, a heliac in Australia, achieved H-transition characteristics.

The H-mode could be realised in all major versions of helical confinement irrespective of the details of their magnetic configuration. The H-mode of helical systems demonstrates its ubiquitous nature. Major differences to tokamaks are the effects of the 3-dimensionality of the system like orbit losses due to the helical ripple, the explicit role of the electric field in transport, and the damping of toroidal rotation. The H-mode in tokamaks is realised in systems with strong positive magnetic shear, in W7-AS and in TJ-II in systems with low magnetic shear, and in the heliotrons CHS and LHD in systems with strong negative shear. More of the H-mode physics in helical systems is presented in ref. [118] and [119].

4.2. Understanding of the H-mode¹²⁰

The first step in understanding the mechanisms behind the sudden L-H transition was the recognition of a transport barrier forming at the very plasma edge [121]. That this rather obvious feature of the H-mode has not been recognised right away had to do with the low quality of diagnostics then in comparison to the standard nowadays. The chance to better understand anomalous transport via the L-H transition with its sharp spatial and temporal features was a major drive toward the creation of new diagnostic techniques with much improved resolution capabilities. The SX-ray diagnostics consisting of an array of viewing cords provided the best resolution at ASDEX and had the capability to follow the thermal pulses resulting from sawteeth starting in the core and travelling across the separatrix into the SOL. After beams had been turned on e.g. in a low-q discharge, sawteeth generally slowed down but grew in amplitude in the L-phase. If an H-transition happened during this period – triggered by a sawtooth larger than any of its predecessors – the thermal wave was found to stagnate at the separatrix and to grow in amplitude but not propagate into the SOL any longer unlike the sawteeth before the transition¹²². At the H-transition the SOL parameters basically collapsed within a sub-ms time scale. This observation led to the notion of an edge transport barrier – a zone of improved confinement right at but within the separatrix [2]. Magnetic measurements with pick-up probes at the plasma edge showed a strong reduction in turbulence level pointing to the possible cause for the lower edge transport. Plasma profiles developed edge pedestals, which are a characteristic feature of the H-mode. The edge gradients are not stably limited by transport rather repetitively hit a critical stability limit. ELMs appeared as a consequence of the steep pressure gradient and high current density within the pedestal [¹²³, ¹²⁴].

The improvement of confinement in the H-mode was not restricted exclusively to the edge. As ASDEX [125] and PDX [126] showed first, confirmed later by others, also the core transport was

¹¹⁶ F. Sano et al., *Journal of Plasma Fusion Research* 79 (2003) 1111.

¹¹⁷ T. Estrada et al., *Contrib. Plasma Phys.* 50 (2010) 501.

¹¹⁸ F. Wagner, *Plasma Phys. Control. Fusion* 48 (2006) 217.

¹¹⁹ A. Fujisawa, *Plasma Phys. Control. Fusion* 45 (2003) R1.

¹²⁰ J. W. Connor and H. R. Wilson, *Plasma Phys. Control. Fusion* 42 (2000) R1.

D.J. Ward, *Plasma Physics Control. Fusion* 38 (1996) 1201.

K. Itoh, *Plasma Physics Control. Fusion* 36 (1994) A307.

¹²¹ F. Wagner et al., *Phys. Rev. Letters* 53 (1984) 1453.

¹²² on TCV, the sawtooth triggered transition happens generally after the thermal wave has reached the boundary region [Y. R. Martin et al., *Plasma Phys. Control. Fusion* 46 (2004) A77].

¹²³ H. Zohm, *Plasma Phys. Control. Fusion* 38 (1996) 105.

¹²⁴ J. W. Connor et al., *Phys. Plasmas* 5 (1998) 2687.

¹²⁵ G. Becker et al., *Nuclear Fusion* 23 (1983) 1293.

reduced following, however, a slow time scale of the order of the confinement time. JET has shown that this improvement is a corollary of the modified edge conditions the broader density profiles resulting from them [127].

The initial view on the H-mode was that the ohmic confinement had been restored and the L-mode was a short-lived accident. The ohmic heating was attributed a special quality because the electron temperature formed a link between current and pressure profile speculatively allowing an adjustment of stability requirements and transport resulting – hypothetically – in better confinement. But the discovery of the H-mode under ohmic conditions stopped such speculations. K. H. Burrell wrote in his 89 paper [128]: “At plasma currents between 2.0 and 2.5 MA, we have found that energy confinement time in H-mode can exceed the saturated Ohmic confinement time by more than a factor of two...” Hence, the H-mode is a confinement branch in its own right.

Facing the complexity of the H-transition – obvious from the parameter dependence of the power threshold or the recommendations on the “how to get it” recipe list - it was evident that the physics is rather involved and its understanding required the joint effort of experiment, theory, and modelling. The regular exchange between these communities was institutionalised in the H-mode workshop series which was initiated by the DIII-D team with the first meeting in 1987 in San Diego. The most recent H-mode workshop, the 15th of its series, was held in IPP, Garching, Oct. 2015.

The task of theory was and still is to identify the mechanism acting at the edge with the potential to reduce the level of turbulence and the consequence that confinement improves and to identify the critical parameters or conditions which initiates the transition. In principle, an instability causing the anomalous transport at the edge of an L-mode plasma could be stabilised by the gradual change of the edge plasma parameters driven by increased heating power up to a critical stability condition. Many experimental observations would indeed support such a scheme. Therefore, in the pioneering period of H-mode transition theory, mostly in the 90ies, all thinkable drift-wave and magnetic instability forms were perused and attractive stability conditions were indeed identified. It is not the place here to go into any physics details as specifically an excellent review on this topic – “A review of theories of the L-H transition” – exists [129] summarizing the status up to 2000. One example – attractive in itself - may be illustrative enough. The first ideas to explain the H-mode concentrated on the obvious, the edge divertor configuration with one or two X-points and the logarithmic increase of q toward the separatrix. C. M. Bishop [130] showed that the plasma edge can enter the 2nd stability regime owing to the elevated edge electron temperature and higher edge current density if the X-points, defining the separatrix, are located in the good curvature region. The experiments showed, however, that H-mode access was possible at higher resistivity with less competitive edge parameters away from the stability limit of ideal ballooning modes [131]. And later, the H-mode could also be realised in plasmas with

¹²⁶ S. M. Kaye et al., in Proc. 11th European Conference on Controlled Fusion and Plasma Physics, Aachen, Germany, 1983 (European Physical Society, 1983) Part I, 19.

¹²⁷ J. E. Kinsey, Nuclear Fusion 39 (1999) 539.

¹²⁸ K. H. Burrell et al., Plasma Physics and Control. Fusion 31 (1989) 1649.

¹²⁹ J. W. Connor and H. R. Wilson, Plasma Phys. Control. Fusion 42 (2000) R1.

¹³⁰ C. M. Bishop, Nuclear Fusion 26 (1986) 1063.

¹³¹ O. Gruber et al., in Proc. 11th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Kyoto, 1986 (IAEA, Vienna 1987) Vol. 1, 357.

limiter configuration without the specifics of the separatrix boundary [132] or in JT-60 with the X-point located at the bad curvature side [133].

An alternative possibility to considering isolated instabilities, which are ultimately stabilised, is the notion of a bifurcating transition – multi-valued solutions exist for the same equilibrium flux, one with high transport rates and low edge gradients and the opposite case – low transport and steep gradients [134]. At the transition, the plasma jumps from the low to the high confinement branch. The fast time scale of the transition and the observation of a hysteresis in the sequence of states – L-mode, transition and, after the auxiliary heating power has been turned down, the H to L back transition, point to a highly non-linear process underlying the bifurcation.

A parameter moved into the centre of tokamak research which up to then was not of much explicit relevance – the radial electric field ¹³⁵. At the IAEA conference in 1984, R. J. Taylor had the question after the talk of M. Keilhacker: “Now, if it is a radial barrier, is it related to the radial electric field?” At the time of the conference, the question could not be answered as no experimental evidence was available. It is not surprising that “stellarator people” like S.I. and K. Itoh and K. C. Shaing explored the ambi-polarity conditions at the edge of tokamaks in more detail. In stellarators with 3-dimensional flux surface geometry, collisional transport depends explicitly on the radial electric field, which acts as drive for the radial fluxes and determines the transport coefficients. Therefore, the role of the electric field has always been of interest in stellarator research and stellarator theory has demonstrated the existence of branches with different ambi-polarity conditions - the electron and the ion root depending on the dominant particle loss channel [136] - before CHS and W7-AS could verify this [137] in the experiment.

For axi-symmetric conditions (tokamak), E_r and plasma flow velocity are linked together as expressed e.g. in the radial force balance but they are not specified separately. Under neo-classical conditions and for steady-state, the poloidal flow velocity $v_{\theta}^{n-cl} \sim \nabla T_i$. Transient, non-ambi-polar conditions with $v_{\theta} > v_{\theta}^{n-cl}$ give rise to radial currents which damp the flow back to the neo-classical level.

For E_r to play a prominent role, a non-ambi-polar process must act at the plasma edge of tokamaks, which ultimately causes a deepening of the electric field. S.-I. and K. Itoh were the first in 1988 [138] to explore the role of the electric field in the L-H transition. They considered the loss of trapped ions at the plasma edge from a radial range corresponding to the ion banana width together with non-ambi-polar turbulent electron losses. The H-transition happens when a critical condition is met and has the character of a hard bifurcation displaying a hysteresis. The electric field becomes more positive improving the confinement of electrons.

The theory by K.C. Shaing and E.C. Crume, published in 1989 [139] also considered - like Itohs` theory - banana ion losses from the edge plasma under low collisionality conditions. The spin-up of the edge poloidal flow due to a radial ion current is balanced by parallel viscosity. In this theory, however, the electric field should become more negative at the transition. Both theories – Itohs` and

¹³² H. Matsumoto et al., Nuclear Fusion 27 (1987) 1181.

¹³³ H. Nakamura et al., Nuclear Fusion 30 (1990) 235.

¹³⁴ K. Itoh, S.-I. Itoh, and A. Fukuyama, “Transport and Structural Formation in Plasmas”, IOP Publishing, Bristol, 1999.

¹³⁵ a tutorial on the electric field and its role is part of the paper: U. Stroth et al., Plasma Phys. Control. Fusion 53 (2011) 024006.

¹³⁶ H.E. Mynick and W.N.G. Hitchon, Nuclear Fusion 23 (1983) 1053.

¹³⁷ H. Idei et al., Phys. Rev. Letters 71 (1993) 2220.

V. Erckmann, et al., in Proc. 16th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Montreal, 1996 (IAEA, Vienna 1997) Vol. 2, 119.

¹³⁸ S.-I. Itoh and K. Itoh, Phys. Rev. Letters 60 (1988) 2276.

¹³⁹ K.C. Shaing and E.C. Crume, Phys. Rev. Letters 63 (1989) 2369.

Shaing's - were consecutively presented at the 1988 IAEA conference [140] one proposing an electron the other an ion root solution to meet edge ambi-polarity. Shaing, the second speaker, ended his presentation by stating: "the experiment has to decide about the sign of the radial electric field".

As we will see, the radial electric field plays a crucial role in the L-H transition. Therefore, both the momentum balance and, as the ion pressure gradient is involved, also the power balance equation enter [141]. Both neo-classical properties and turbulent processes come into play. Many non-ambi-polar conditions can be constructed at the plasma edge, which could have an effect on the radial force balance. They have been summarized by Itoh and Itoh [142] in the form of $\epsilon_0 \epsilon_{\perp} / e \, dE_r / dt = \Sigma \Gamma^{\text{non-amb}}$. The currents on the right side can originate from ion losses into the plasma boundary or be caused by forces like the neo-classical parallel and poloidal viscosity intrinsic to toroidal geometry with a strong non-linear dependence on plasma flow or turbulent ones like turbulent Reynolds stress or those which derive from the proximity to open field lines like the losses of loss-cone ions, neutral collisions of electrons and ions or wave momentum losses across the separatrix - processes which enforce an ambi-polar response.

The challenge of the H-mode – to measure sophisticated plasma parameters at the plasma edge – ultimately with a time resolution in the range of 100 μs or better and a spatial resolution in the mm range was specifically accepted by the DIII-D team. Till the beginning of the 90ies, DIII-D has contributed with significant experimental evidence which helped theory to develop a deeper understanding of the L-H transition and the H-mode, ending in a complete paradigm change in the understanding of turbulent transport [143]. Initially, DIII-D contributed with the following crucial findings:

- The radial electric field, which is slightly positive in the core, slightly negative at the periphery and again positive in the SOL develops a deep negative well at the location of the transport barrier within 500 μsec of the transition [144]. The electric field confines the ions. DIII-D established that the E_r -field change introducing strong $E \times B$ shear flow in the edge region is a fundamental property of the H-mode.
- The density fluctuations drop within the transport barrier by at least a factor of 2 within 100 μsec of the transition identified precisely by the drop in D_{α} radiation [145]. This observation posed an enormous challenge to theory because the turbulence decreased in a region where the turbulence drive, the pressure gradient, forming the transport barrier, sharply increased.
- The particle flux, measured with Langmuir probes in ohmic discharges via the fluctuating constituents, density and $E \times B$ velocity, confirmed the indirect conclusions on improved global particle confinement [146] and were a direct proof of the impact of the drop in density fluctuations on radial flux and confinement.

¹⁴⁰ K.C. Shaing, in Proc. 12th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Nice, 1988 (IAEA, Vienna 1989) Vol. 2, 13.

K. Itoh, *ibid* p. 23.

¹⁴¹ J. D. Callen et al., Phys. Plasmas 17 (2010) 056113.

¹⁴² K. Itoh and S.-I. Itoh, Plasma Phys. Control. Fusion 38 (1996) 1.

¹⁴³ K. H. Burrell, Phys. Plasmas 4 (5) 1499 and references therein.

K. Lackner et al., Plasma Phys. Control. Fusion 31 (1989) 1629.

¹⁴⁴ R. J. Groebner et al., Phys. Rev. Letters 64 (1990) 3015.

¹⁴⁵ E. J. Doyle et al., Phys. Fluids B3 (1991) 2300.

¹⁴⁶ R. A. Moyer et al., Phys. Plasmas 2 (1995) 2397.

J. W. Connor, himself a theoretician, writes in his review paper “A review of theories of the L-H transition” [147] “Remarkably, changes in E_r at the transition were predicted theoretically [41]¹⁴⁸ before they were observed experimentally; the observation of these has led to their inclusion in many later theories.” The first radial electric field measurements were reported by R. Groebner at the 16th EPS conference on plasma physics in March 1989 in Venice [149] and published in June 1990 [150]. At the L-H transition, the radial electric field, measured spectroscopically through the pressure gradient and the $E \times B$ flow of impurities via the Doppler shift of their lines, became more negative. The general evidence is that right at the transition the poloidal flow velocity v_θ of impurities contributes most to the E_r -field drop [151]. Specifically the ohmic H-mode showed that external momentum input is not required to induce the E_r -field change. Figure 2a compares the radial electric field in DIII-D shortly before and shortly after the L-H transition [152]. The development of a deep E_r -well at the plasma edge was later confirmed by all devices which studied this phenomenon. The edge E -field measurements from JFT-2M followed shortly after the Groebner paper in September of the same year [153]. The ASDEX-team confirmed these results in 1992 [154] and the W7-AS one reproduced this striking feature of the H-mode in 1998 [155] in a stellarator. For a long time, the increase in poloidal flow was not confirmed by JET [156] but recently after better alignment of the diagnostic optics, also JET observed poloidal spin-up of tracer impurities [157]. An independent and elegant technique to demonstrate the development of E_r at the plasma edge without resorting to poloidal flow measurements of impurities was developed at ASDEX Upgrade. The edge electric field affected the confinement of fast neutral beam heating ions, which happened to be trapped in the magnetic ripple of the discrete toroidal field coils during their slowing-down phase [158]. These ions are quickly lost by ∇B drift least an electric field improves their confinement. The rise of the energetic charge exchange flux at the H-transition and the delay time of this rise for more energetic ions could be used to demonstrate with a time resolution of 50 μ s the drop of the radial electric field right at the LH-transition.

The development of a deep E_r -field well at the very plasma edge starting at the separatrix and extending a few cm into the plasma is the most conspicuous feature of the transport barrier. Several obvious questions follow this finding – what are the actual flow conditions of the plasma ions subject to the E_r field as determined from the impurity tracers - does the poloidal flow remain at the neo-classical level during the transition, if not - what is the non-ambi-polar process acting at the plasma edge - why does the electric field or, equivalently, the $E \times B$ flow reduce the level of turbulence – how can the role of E_r be translated into a power threshold – and many more attractive questions for fusion scientists.

¹⁴⁷ J.W. Connor and H.R. Wilson, Plasma Phys. Control. Fusion 42 (2000) R1.

¹⁴⁸ S.-I. Itoh and K. Itoh, Phys. Rev. Letters 60 (1988) 2276.

¹⁴⁹ R. J. Groebner et al., in Proc. 16th European Conference on Controlled Fusion and Plasma Physics, Venice, 1989 (European Physical Society, Petit-Lancy, Switzerland, 1989), Vol. 13B, p. 245.

¹⁵⁰ R. J. Groebner et al., Phys. Rev. Letters 64 (1990) 3015.

¹⁵¹ P. Gohil et al., Nuclear Fusion 38 (1998) 93.

¹⁵² K. H. Burrell, Phys. Plasmas 6 (1999) 4418

¹⁵³ K. Ida et al., Phys. Rev. Letters 65 (1990) 1364.

¹⁵⁴ A. R. Field et al., Nuclear Fusion 32 (1992) 1191.

¹⁵⁵ J. Baldzuhn et al., Plasma Phys. Control. Fusion 40 (1998) 967.

¹⁵⁶ N. C. Hawkes et al., Plasma Phys. Control. Fusion 38 (1996) 1261.

¹⁵⁷ Y. Andrew et al., EPL 83 (2008) 15003.

¹⁵⁸ W. Herrmann and ASDEX Upgrade Team, Phys. Rev. Lett. **75** (1995) 4401.

This catalogue of questions is not yet worked off in all possible details. In a key paper, which appeared in 1990 [159], H. Biglari, P.H. Diamond and P.W. Terry proposed a mechanism and a criterion for turbulence suppression which later, after general acceptance, was called the BDT criterion. The basic idea is that turbulent eddies causing L-mode transport are subject to poloidal flow at the edge. If this flow, actually the $E \times B$ flow as recognised right away, varies radially [160] eddies are stretched and tilted and broken up to smaller and finally less transport relevant entities. More specifically, the fluctuations are decorrelated. A stabilising impact of sheared flows has already been pointed out by B. Lehnert in 1966 [161]. He wrote: “Thus, a non-uniform velocity should have a stabilizing tendency by “smearing out” the flute disturbance.”

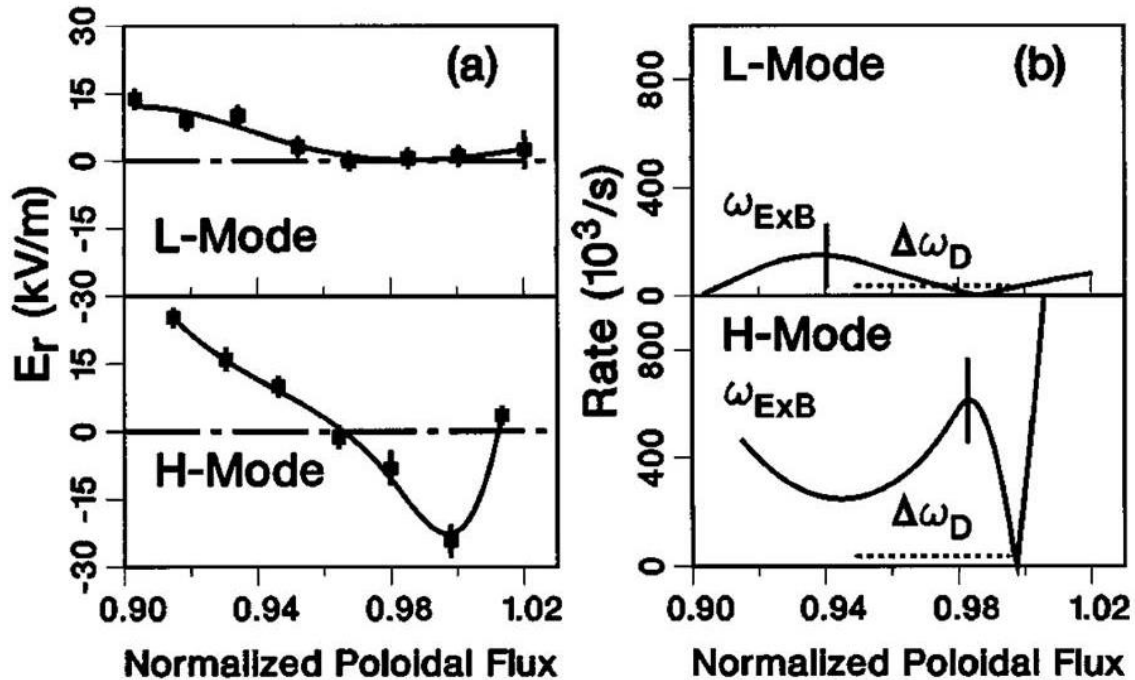


Figure 2. a) Plotted is the radial electric field in DIII-D shortly before and shortly after the L-H transition; Fig. 2b) Compared are $E \times B$ shearing rate $\omega_{E \times B}$ with the turbulence de-correlation time $\gamma = \Delta\omega_D$ (see equ. 2) for the L- and H-mode phases shown in Fig. 2a. For details see [162, Fig. 5].

The BDT mechanism was first verified in TEXT ohmic discharges [163]. Within the natural $E \times B$ shear flow layer at the edge the turbulence correlation times and the fluctuation level were reduced whereas the density gradient was increased. DIII-D demonstrated the reduction of the radial correlation length of edge turbulence at the transition from the L- to the H-mode confirming an important prediction of the theory [164]. The BDT criterion represents a quantitative relation for stability by sheared flow, which is met when the shearing rate $\omega_{E \times B}$ of the flow field is larger than the maximal linear growth rate γ_{\max} of the least stable mode: $|\omega_{E \times B}| > \gamma_{\max}$ (2); $\omega_{E \times B} \sim \partial E_r / \partial \psi$; the sign of the field variation is irrelevant. It was shown first by DIII-D [165] and later at many other devices that

¹⁵⁹ H. Biglari, P.H. Diamond and P.W. Terry, Phys. Fluids B 2 (1990) 1.

¹⁶⁰ B. A. Carreras et al., Phys. Fluids B5 (1993) 1491.

¹⁶¹ B. Lehnert, Phys. Fluids 9 (1966) 1367.

¹⁶² K. H. Burrell, Phys. Plasmas 6 (1999) 4418.

¹⁶³ Ch. P. Ritz et al., Phys. Rev. Letters 65 (1990) 2543.

¹⁶⁴ K. H. Burrell, Phys. Plasmas 6 (1999) 4418.

¹⁶⁵ K. H. Burrell, Phys. Plasmas 6 (1999) 4418.

this condition was fulfilled within the edge transport barrier with strongly reduced turbulence level (see Fig. 2b). The turbulent ion transport, based on ITG driven instabilities is more affected by shear flow than the shorter wavelength ETG driven ones. It is a general observation that cases with improved confinement based on the reduction of the ion transport are more frequently observed than those on the electron one. The shearing rate can be large enough to totally quench turbulence placing transport, generally ion transport, at the collisional limit. But intermediate states are possible where the shearing rate reduces transport without completely annihilating it.

The BDT model and criterion address only one important aspect of the H-mode – the mechanism for reducing edge turbulence via sheared flow. It does not provide the full understanding of the H-transition. The additional question is the origin of the radial electric field developing at the plasma edge in a spontaneous step. The simplest understanding would resort to the growing ion pressure gradient within the edge barrier which is a constituent of the radial force balance determining E_r : $E_r = \nabla p_i / Z_i e n_i - v_\theta B_\phi + v_\phi B_\theta$ (3). E_r becomes more negative with pressure gradient ∇p_i and poloidal flow velocity v_θ and more positive with toroidal velocity v_ϕ . Internal triggers like sawteeth inducing the H-mode point toward the pressure gradient as the reason for E_r . All three constituents can introduce sheared flow. The initial flow and E_r -field measurements of DIII-D showed a delay between the spin-up of poloidal impurity flow – the most striking flow feature - and the increase of the impurity edge ion temperature gradient [166]. The drop in E_r inside the separatrix coincided within 500 μ s with the step of the D_α radiation - the transition monitor. The ion temperature gradient as proxy for the ion pressure gradient followed, however, along the slower confinement time. According to this observation, confirmed by others [167], the mean flow from the ion pressure gradient was not the primary cause for the transition.

The radial electric field deduced from the poloidal flow of impurities was found to be beyond the neo-classical level in DIII-D [168] pointing toward an additional drive term in the poloidal momentum balance. It was conjectured that turbulent Reynolds stress (RS) could spin up transiently the poloidal flow beyond the neo-classical level [169] adding the so-called turbulence driven zonal flow (ZF) to the mean $E \times B$ flow of the ion pressure gradient¹⁷⁰. The turbulent RS is generated by the high level of turbulence in the L-phase as soon as the radial and poloidal velocity components \tilde{v}_r and \tilde{v}_θ develop coherence.

In toroidal geometry, the electric field component contributed by RS comes in the form of low-frequency flows, the zonal flows, or in the form of higher-frequency flows, so called Geodesic Acoustic Modes (GAMs) where compressibility is involved. ZFs and GAMs are radially localised space-charge perturbations with varying radial field direction and with $m=0$ and $n=0$ structure. Low-frequency zonal flows were first demonstrated by S. Coda in 2001 [171] and GAMs by M. Jakubowski

¹⁶⁶ R. A. Moyer et al., Phys. Plasmas 2 (1995) 2397.

¹⁶⁷ Y. H. Xu et al., Phys. Rev. Letters 84 (2000) 3867.

T. Estrada et al., Phys. Plasmas Control. Fusion 51 (2009) 124015.

G. D. Conway et al., Phys. Rev. Letters 106 (2011) 065001

G. S. Xu et al., Phys. Rev. Letters 107 (2011) 125001.

¹⁶⁸ Y. B. Kim et al., Phys. Fluids B3 (1991) 2050.

¹⁶⁹ B.A. Carreras et al., Phys. Fluids B3 (1991) 1438.

P.H. Diamond and Y.B. Kim, Phys. Fluids B3 (1991) 1626.

¹⁷⁰ the term “zonal flow” is borrowed from meteorology and oceanography denoting spatially restricted flow pattern e.g. zonal flows generated by baroclinic turbulence where sheared flow induces eddy tilting and Reynold stress is the mechanism to force zonal flows [A. F. Thompson and W. R. Young, Jour. Atmospheric Sciences, 64 (2007) 3214].

¹⁷¹ S. Coda et al., Phys. Rev. Letters 86 (2001) 4835.

[172] in the edge of DIII-D; A. Fujisawa proved their electrostatic nature and identified their geometry in the core of CHS heliotron using a dual heavy-ion-beam diagnostics [173]. The appearance of zonal flows in both forms of realisation demonstrated the non-linear coupling mechanism between small-scale turbulence and $E \times B$ flow. Both driven flow forms need turbulence drive as provided in the L-phase and they consequently disappear in the H-phase. A seminal review on zonal flows in fusion plasmas is written by P. H. Diamond, S.-I. Itoh, K. Itoh and T. S. Hahm published in 2005 entitled “Zonal flows in plasma – a review” [174].

The experimental verification of the spontaneous self-regulating process of drift wave-type turbulence and ZFs via RS was an important contribution of smaller laboratory experiments to the understanding of the H-mode of the large fusion flagships. That the RS can be a sizable effect in the momentum balance driving macroscopic flows was demonstrated in the linear device CSDX [175], in the Heliac H-1 [176], in the Torsatron TJ-IU [177] at CIEMAT in Madrid and with more detail in the same device operated later as TJ-K at the university Kiel [178]. CHS showed how the combined effect of ZF and mean flow affects the high-frequency branch of the turbulence and established such the causality between flow and turbulence [179]. A complete documentation on sheared flows, their non-linear interaction with turbulence, the spectral flow of energy in this system and the consequences on confinement of H-1 Heliac plasmas was published by M. G. Shats and co-workers [180]. The role of this process for the H-mode transition was demonstrated by HT-6M tokamak in 2000 [181] and specifically its transiently increasing effectiveness just prior to the transition was shown in 2001 by DIII-D in [182].

The coupling between the different temporal and spatial scales of turbulence and macroscopic flows can be considered as a 3-wave interaction problem, which allowed to identify the energy flow from the small turbulence scales to the macroscopic flow in the frequency domain [183] and in k-space [184]. H-transitions mediated by low-frequency ZFs were retraced along this self-regulating mechanism and the BDT criterion by [185] and via GAMs by [186]. On the background of all these data K. H. Burrell could conclude in his review paper on this topic [187]: “Considering all the experimental data, there is significant evidence that zonal flows exist in toroidal plasmas. In addition, there is evidence that both the low frequency zonal flows and GAMs can affect the higher frequency turbulence”.

The efforts to understand the H-mode and the LH-transition has produced significant understanding of anomalous transport and has specifically developed a new paradigm for turbulent transport.

¹⁷² M. Jakubowski et al., Phys. Rev. Letters 89 (2002)265003.

¹⁷³ A. Fujisawa et al., Phys. Rev. Letters 93 (2004) 165002.

¹⁷⁴ P. H. Diamond, S.-I. Itoh, K. Itoh and T. S. Hahm, Plasma Phys. Control. Fusion 47 (2005) R35.

¹⁷⁵ C. Holland et al., Phys. Rev. Letters 96 (2006) 195002.

¹⁷⁶ M. Shats and W. Solomon, Phys. Rev. Letters 88 (2002) 045001.

¹⁷⁷ E. Sánchez et al., Contributions to Plasma Physics 38 (1998) 93.

¹⁷⁸ P. Manz et al., Phys. Rev. Letters 103 (2009) 165004.

¹⁷⁹ A. Fujisawa et al., Plasma Phys. Control. Fusion 48 (2006) S 205.

¹⁸⁰ M. G. Shats et al., Phys. Rev. E 71 (2005) 046409.

¹⁸¹ Y.H. Xu et al., Phys. Rev. Letters 84 (2000) 3867.

¹⁸² R. A. Moyer et al., Phys. Rev. Letters 87 (2001) 135001.

¹⁸³ H. Xia and M.G. Shats, Phys. Rev. Letters 91 (2003) 155001.

¹⁸⁴ P. Manz et al., Phys. Rev. Letters 103 (2009) 165004

¹⁸⁵ P. Manz et al., Phys. Plasmas 19 (2012) 072311.

¹⁸⁶ G. D. Conway et al., Phys. Rev. Letters 106 (2011) 065001.

¹⁸⁷ K. H. Burrell, Plasma Phys. Control. Fusion 48 (2006) A347.

Confinement is not simply based on transport caused by fully developed turbulence of regime-dependent instabilities but by a self-regulated state saturated by self-driven flows [188].

In 2-dimensional turbulence where turbulent eddies can merge because vortex tubes do not stretch, the spectral flow of energy is from smaller scales to larger ones (inverse cascade) till an $m=0, n=0$ potential structure of the size of the provided geometry, the ZF, is formed [189]. In this phase the turbulent eddies are strained-out - borrowing a technical term from 2-D turbulence in neutral fluids - and transfer effectively energy to the flow [190]. As this flow is sheared it eventually acts back onto the turbulence in a way the BDT criterion suggests. This intermediate step driven by RS reduces the turbulence level, improves the confinement, and allows steeper ion pressure gradients. Thanks to this mechanism the free energy increasing with the heating power is stored in a “reservoir” [191] without intensifying turbulence and increasing transport. The momentum balance plays a significant intermediate role in this stage. The increased ion pressure gradient or the concomitantly enhanced and sufficiently sheared mean flow ensures that the BDT criterion is still met after the trigger period when E_r is now at the neo-classical level again [192]. Therefore, the final state is governed by the edge power balance. In total, a quiescent state of good confinement with high fusion reactor relevance has emerged in a self-organising manner from a state with a high degree of turbulence with little use for the technical objectives of magnetic confinement research.

The chicken-and-egg question of causality in the circular interplay between turbulence and flow may be obsolete because the object is the drift-wave-zonal flow complex. Nevertheless, there are empirical recipes for attaining the H-mode and there is a clear driving agent, the heating power both pointing to a chain of actions. The larger the heating power is, the more probable is the transition and the shorter is the preceding L-phase. In case of DIII-D, causality was indicated with E_r being the lead parameter. It was the first parameter to change after the H-mode. This was checked carefully in H-transitions at low power close to the power threshold when the whole transition process was slowed down. Furthermore, a deeper E_r -minimum led to a shorter transition time [193] and a lower level of turbulence [194].

The leading role of the radial electric field at the edge was finally demonstrated by triggering the H-mode or plasma states with edge transport barriers using biasing probes inserted into the plasma [195] or by biasing divertor target plates [196]. The first relevant experiments were carried out at CCT at UCLA [197], expanded in much detail by TEXTOR tokamak [198]. The theory of plasma biasing is provided in ref. [199]. These experiments clearly demonstrated a phase lag between electric field, applied from the outside, and the reduction of the turbulence level and the increase of the edge pressure gradient. The agent is the electric field. JFT-2M confirmed this result by demonstrating the

¹⁸⁸ U. Stroth et al., Plasma Phys. Contr. Fusion 53 (2011) 024006.

¹⁸⁹ A. Hasegawa and M. Wakatani, Phys. Rev. Letters 59 (1987) 1581.

¹⁹⁰ P. Manz et al., Phys. Rev. Letters 103 (2009) 165004.

¹⁹¹ K. Miki et al, Phys. Plasmas 19 (2012) 092306.

¹⁹² J. Schirmer et al., Nuclear Fusion 46 (2006) S780.

¹⁹³ R. J. La Haye et al., Nuclear Fusion 33 (1993) 349.

R. J. La Haye et al., Nuclear Fusion 35 (1995) 889.

¹⁹⁴ P. Gohil et al., Nuclear Fusion 38 (1998) 93.

¹⁹⁵ R. R. Weynants and G. Van Oost, Plasma Phys. Control. Fusion 35 (1993) B117.

¹⁹⁶ Y. Miura et al., Proc. 16th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Montreal, 1996 (IAEA, Vienna 1997) Vol. 1, 167.

¹⁹⁷ R. J. Taylor et al., Phys. Rev. Letters 63 (1989) 2365.

¹⁹⁸ R. R. Weynants et al., Nuclear Fusion 32 (1992) 837.

¹⁹⁹ V. Rozhanski and M. Tendler, Reviews of Plasma Physics, vol. 18, Consultants Bureau, N.Y. & London, 1996, p147

variation of the power threshold with plasma biasing. When biasing added to the intrinsic E_r , P_{thr} decreased; biasing at opposite polarity increased it [200]. The issue of causality is discussed in detail in [201] for the transition into the H-mode and into other advanced modes of operation.

A more formal way to look at the L to H transition and the H to L back transition was from the point of view of bifurcation theory [202] discriminating between fast and slow transitions and considering intermediate states (dubbed I-phases) where the plasma oscillates between the two equilibrium branches in the form of limit-cycle-oscillations (LCO) [203]. Transitions with extended I-phases could be cultivated experimentally by operating close to the power threshold and thanks to detailed edge measurements the causality between the various parameters involved could be elucidated in quite some detail. Formally, the bifurcation and the associated limit-cycle-oscillations could be described by a predator-prey equation system with the turbulence adopting the role of the prey feeding the sheared $E \times B$ flow which itself plays the role of predator finally killing it [204]. This Ansatz treats the combined flow and turbulence system self-consistently and identifies the phase shift between turbulence and flow in the form of zonal flows or of the equilibrium $E \times B$ flow and highlights their instrumental role for the transition [205]. In the L-phase, the flow is found to lag behind the turbulence level – as expected. In course of the I-phase the LCO slow down. This reflects the fact that the role of the ion pressure gradient for the flow increases and the periods where the decorrelation time $>$ inverse growth rate (equ. (2)) are prolonged. The continuously increasing ion pressure ultimately stabilises the situation. After this prelude the mean background flow ensures the low turbulence edge state as long as power is put into the system. There are two predators – ZFs when the hunt starts and the mean flow, when the prey resigns. This sequence of affairs is presented in detail in [206] and confirmed by the results of many other devices [207].

The historical account of elucidating the physics of the H-mode comes to an end here. The last chapter summarises to some extent the situation as described during the 15th H-mode workshop this year in Garching. Many excellent detailed results are covered by the special issue on “Experimental Studies of Zonal Flows and Turbulence” [208]. Nevertheless, as always in research, hardly anything is final so that the history books could be closed for ever. The observed RS was not sufficiently strong to trigger the H-transition in all cases [209]. More studies are necessary to elucidate the direct route via the equilibrium flow by the pressure gradient avoiding the intermediate step of the ZF. Sawtooth or gas-puff triggered transitions might point into this direction.

E.J. Doyle [210] of DIII-D concluded in 1992: “That the change in edge profiles is a consequence of the change in E_r , and not vice versa, has recently been shown by analysis of fast time resolution CER

²⁰⁰ T. Shojij et al., in Proc. 14th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Würzburg, 1992 (IAEA, Vienna 1993) Vol. 1, 323.

²⁰¹ K. H. Burrell, Physics of Plasmas 6 (1999) 4418.

²⁰² S.-I. Itoh and K. Itoh, Phys. Rev. Letters 60 (1988) 2276.

²⁰³ T. Estrada et al., Europhys. Letters 92 (2010) 35001.

²⁰⁴ P.H. Diamond et al., Phys. Rev. Letters 72 (1994) 2565.

E.J. Kim and P.H. Diamond Phys. Rev. Letters 90 (2003) 185006.

²⁰⁵ P. Manz et al., Phys. Rev. E 82 (2010) 056403.

²⁰⁶ G. D. Conway et al., Phys. Rev. Letters 106 (2011) 065001;

²⁰⁷ L. Schmitz et al. Phys. Rev. Letters 108 (2012) 155002 and references therein.

²⁰⁸ Plasma Phys. Control. Fusion 48 (2006) #4.

²⁰⁹ T. Kobayashi et al., Phys. Ref. Letters 111 (2013) 035002.

J. Cheng et al., Nuclear Fusion 54 (2014) 114004.

²¹⁰ E.J. Doyle et al., in Proc. 14th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Würzburg, 1992 (IAEA, Vienna 1993) Vol. 1, 235.

²¹¹ data. As described in Ref. [14] [212], the increase in density and temperature gradients in the edge lag the changes in E_r , and thus cannot be the cause of the change in E_r .”

M. Cavedon, who reported at the 2015 H-mode workshop, writes in his recently submitted paper [²¹³]: “We have provided experimental evidence of the role of the neoclassical flows in the L– H transition physics. Although it has been shown turbulence-zonal flow interaction is present in toroidally confined plasmas, we do not have evidence that it contributes substantially in the phases investigated.” And Y. Andrew from JET goes a step further and reported in 2008 [214]: “These data ²¹⁵ suggest that the development of significant shear in E_r arises as a consequence of the high confinement phase of the plasma and is not required to enter or maintain the H-mode on JET. This important result indicates that $E \times B$ shear suppression of turbulence does not trigger the transport barrier formation, although it may well play a role in transport barrier sustainment and dynamics.” Different routes seem to lead to the H-mode. More research is still necessary. These lead-authors express the views of their co-authors. In [216] there is a detailed analysis of the spatial and temporal resolution required to seriously address the question of a precursor period to the H-mode transition.

Another recent observation may add to the affluence of H-mode transition mechanisms concerning the parallel flow which played up to now a negligible role at the edge. Recent flow measurements in the L-mode of the plasma species circumventing impurities as tracers showed that the parallel flow suddenly increases toward the edge [217]. This is explained by ion-orbit losses. These observations and conclusions are too new to be dealt with here in detail and may enter the next history account on the “story” of improved confinement scenarios.

4.3. Improving the H-mode

All experimental teams try to further improve the H-mode confinement beyond the typical factor of two in τ_E above the L-mode. Several further improved confinement regimes came about surreptitiously while pursuing other priorities – e.g. starting additional heating early in the discharge during current ramp-up to economise on stored energy in the primary transformer - or developing low- β_p scenarios with high bootstrap current j_{bst} [2] for steady-state operation – or using impurity radiation to ameliorate exhaust conditions and to protect the inner wall. Another line of research dealt with the nuisance which unfortunately accompanies the H-mode, viz. edge localised modes (ELMs [218]). In a repetitive relaxation process a large amount of energy ($\Delta W/W \sim 5-10\%$) is released within a few 100 μs . The resulting power flux onto the divertor target plates is difficult for engineers to handle even with the best material and cooling technologies. There is a tremendous effort to avoid ELMs and the inherent instabilities by external means – e.g. resonant and non-resonant techniques using saddle coils, so called resonant magnetic perturbation coils with different toroidal and poloidal periodicities [2]. These coils demonstrated their efficiency in several experiments but this technique cannot yet guarantee their complete avoidance [219]. But suppressing ELMs can be a double-edged matter. Without ELMs, the confinement may be too good for impurities and the plasma can get increasingly dirty. As the integration of such saddle coils into a fusion reactor, located close to the plasma surface, pose a

²¹¹ CER = charge exchange recombination spectroscopy

²¹² K.H. Burrell et al., Plasma Phys. Control. Fusion 34 (1992) 1859.

²¹³ M. Cavedon et al., Nuclear Fusion 57 (2017) 014002.

²¹⁴ Y. Andrew et al., Europhys. Letters 83 (2008) 15003.

²¹⁵ those presented in the paper.

²¹⁶ K. H. Burrell, Phys. Plasmas 6 (1999) 4418.

²¹⁷ W. M. Stacey and B.A. Grierson, Nuclear Fusion 54 (2014) 073021.

²¹⁸ M. Keilhacker et al., Plasma Phys. Control. Fusion 26 (1984) 1A.

²¹⁹ T. E. Evans et al., Phys. Rev. Letters 92 (2004) 235003.

technical challenge a much better way would be to discover and to develop scenarios without ELMs and, if possible, without having to accept impurity trade-offs.

4.3.1 The VH-mode of DIII-D

Whereas wall boronisation [220] improved the H-mode confinement in ASDEX by nearly a factor of three [221] compared to the L-mode standard [222] this technique improved the confinement in DIII-D up to an H-factor of 3.5. This confinement regime, developed in the early 90ies, was dubbed VH (very high)-mode [223]. Its development necessitated low density in the ohmic phase and higher beam power. Also in the JET case, low recycling wall conditions had been mandatory to access enhanced confinement regimes categorized as VH-modes [224].

VH-mode was realised in DIII-D in the early 90ies in configurations with improved edge stability owing to an increase in triangularity. The VH-mode is generally without ELMs and has a confinement time a factor of up to 3.5 above the L-mode level. The most characteristic feature of the VH-mode is a broader edge transport barrier with the E_r -shear extending from the edge to $\rho \sim 0.6$ resulting in higher pedestal parameters (at gradients close to the stability limit). In the radial range closer to the core, the enhanced toroidal flow contributes to the radial electric field shear. In the broad VH-mode transport barrier, turbulence is suppressed. The BDT-criterion is fulfilled over the complete barrier range. The VH-mode pedestal, broader than the thermal ion banana width, allows the conclusion - as pointed out in [225] - that ion orbit losses cannot be the only seed mechanism for the H-transition.

4.3.2 The CDH-mode of ASDEX Upgrade

In the effort to cope with the power exhaust conditions strongly affected by type-I ELMs, ASDEX Upgrade developed 1995 the so called “completely detached H-mode” (CDH) [226] employing neon puffing [227]. Under conditions where the plasma stayed detached and a high power fraction was radiated off (up to 90%) the confinement did not degrade. Also the ELMs stayed small and were categorized as type-III ELMs and their power was dissipated at high density divertor operation. Later a significant improvement of confinement in N_2 seeded deuterium plasmas typically by 25% was noted [228]. The improved confinement was caused by an increase of the ion energy content but unlike other cases with impurity seeding [see e.g. chapt. 3.2.5] the improvement was not correlated with a peaking of the density profile. DIII-D repeated these experiments and observed a reduction of the ion transport also in the core of the plasma specifically an improvement of momentum transport. There is evidence that the improvement is due to $E \times B$ shear flow stabilisation within the core region [229]. In case of JT-60U, the ion energy content profited from Ar-seeding leading to improved H-mode confinement. This improvement was also not attributed to density profile changes [230].

²²⁰ J. Winter et al., Journal Nuclear Materials 162-164 (1989) 713.

²²¹ F. Wagner et al., in Proc. 13th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Washington DC, 1990 (IAEA, Vienna 1991) Vol. 1, 277.

²²² P.N. Yushmanov et al., Nuclear Fusion 30 (1990) 1999.

²²³ G. L. Jackson et al., Phys. Rev. Letters 67 (1991) 3089.

²²⁴ K. Thomsen et al., Plasma Phys. Control. Fusion 36 (1994) 7A.

²²⁵ P. H. Diamond et al., Phys. Rev. Letters 72 (1994) 2565.

²²⁶ O. Gruber et al., Phys. Rev. Letters 74 (1995) 4127.

²²⁷ O. Gruber et al., Phys. Rev. Letters 74 (1995) 4127.

²²⁸ O. Gruber et al., Nuclear Fusion 49 (2009) 115014.

²²⁹ G. L. Jackson et al., Nuclear Fusion 42 (2002) 28.

²³⁰ S. Higashijima et al., Journal Nuclear Materials 13 (2003) 1123.

4.3.3 The Improved H-mode of ASDEX Upgrade

The originally dubbed “Improved H-mode” was published by ASDEX Upgrade in 1999 [231]. The improvement came about by first enhancing the stability of the magnetic configuration with higher triangularity and by reorienting the NBI system to more off-axis deposition. While the H-mode edge was maintained the core confinement improved owing to a peaking of the pressure profile. The enhancement of the confinement was about a factor three above the L-mode level.

This mode was not steady-state rather the non-inductive current was originally not larger than 20% but it could be maintained for several tens confinement times and also for a few current diffusion times. This quality is the outstanding feature of this regime. The Improved H-mode could be expanded toward higher densities without confinement degradation one normally has to accept when approaching the density limit. Also the ELMs became smaller and less critical at higher densities.

The improved H-mode requires a subtle trade-off between current and pressure profile development so that the central q-value remains shortly above 1. A low level of MHD seems to prevent current penetration to the core. In this case, sawteeth are not present and neo-classical tearing modes not triggered avoiding the otherwise inevitable β reduction. After some back-and-forth, it was clarified that the temperature profiles remained canonical still subject to the critical gradient conditions of the underlying instabilities. The highest value of the fusion triple product in ASDEX Upgrade was realised in the “Improved H-mode”.

Two years after ASDEX Upgrade, DIII-D reported on the development of the “Improved H-mode” [232] without specific reference to the ASDEX Upgrade mode but also refraining from inventing a new label. Now, there is consensus that the two regimes share indeed the major characteristics [233]. DIII-D expanded this regime to bootstrap current fractions of about 50% and it demonstrated the need for active particle control. Transport analysis showed the presence of turbulent fractions of ITG, ETG and TEM modes not much reduced by sheared flow. In 2005, JET realised this operational mode also demonstrating its transferability to larger sizes.

4.3.4 The EDA-mode of C-mod, the QH-mode of DIII-D and the I-mode of C-mod

The instabilities underlying ELMs - pressure gradient driven kinetic ballooning and current density driven peeling modes [234] - are triggered by too steep a pressure gradient at the plasma edge. The remaining H-mode transport is too low to prevent hitting the stability limit so that a quasi-steady state arises via the periodic violation of an MHD stability limit. The strategies for suppressing ELMs and thereby improving the H-mode is clear - avoidance of too steep edge gradients obeying the additional condition to prevent an increase of impurity content. It is well known that energy and particle confinement go together in parameter variation as well as in confinement transitions. The density or current scaling under ohmic or auxiliary heating conditions, respectively, and the L/H-mode couple are examples. Several improved regimes without ELMs have been identified where the edge pressure gradient is clamped below the critical instability limit by a quasi- or weakly coherent mode residing at the plasma edge with the beneficial trait to exclusively reduce particle transport leaving energy transport largely unaffected. This is an interesting but not yet well understood constellation. Conventional expectation is that a perturbation like the weakly coherent mode would preferentially increase energy transport via electron convection and to a lesser extent particle transport.

²³¹ R. C. Wolf et al., Plasma Phys. Control. Fusion 41 (1999) B93.

²³² T. C. Luce et al., Nuclear Fusion 41 (2001) 1585.

²³³ A.C.C Sips et al., Plasma Phys. Control. Fusion 47 (2005) A19.

²³⁴ H.R. Wilson et al, Phys. Plasmas 9 (2002) 1277.

C-Mod reported at the 1996 IAEA conference on the development of EDA, the “Enhanced- D_α H-mode” [235]. The denotation comes from the observation of enhanced D_α radiation from the inner SOL beyond the X-point. ELMs were replaced by a quasi-coherent (QC) mode residing at the plasma edge in the outer part of the pedestal, which obviously limited both the edge pressure to below the ELM stability border and the particle confinement maintaining a pure plasma. Stability analysis indicated that the QC-mode was a resistive X-point mode [236] located at the plasma edge. The operational range of the EDA-mode turned out to be somewhat limited to higher densities and q-values and to equilibria with improved stability thanks to higher triangularity. A critical value was found to be the edge electron temperature. Values above 400 eV caused the development of a regular ELMy H-mode. Within these limits, EDA is a steady-state H-mode without the challenge of ELMs on one side or high impurity concentrations on the other.

In 2002, DIII-D went public with an H-mode without ELMs at conventional confinement level discovered in 1999 [237]. This mode was originally established with counter neutral beam injection when additionally strong pumping had been applied [238]. Under these circumstances and with beam fuelling alone, ELMs were absent or rare and small so that the mode was dubbed quiescent H-mode (QH-mode). Because of the so-called edge harmonic oscillation EHO, residing in the gradient region at the plasma edge and driven by it, the particle confinement was low and the QH-mode could be maintained for long periods without the usual corollary of increasing density or impurity content. The energy confinement time did not seem to be affected by this oscillation. The presence of the EHO was found to be crucial. Within the SOL the direct particle transport across the separatrix by the EHO could be demonstrated. If the EHO was annihilated e.g. by large pellet injection, ELMs appeared. EHO in DIII-D is not a single frequency mode but composed of several Fourier-components owing to its spatial structure. EHO is considered to be a resistive peeling-ballooning mode saturated by shear flow below the actual stability limit which itself is further improved by plasma shaping [239].

In 2003, ASDEX Upgrade realised the QH-mode [240], JT-60 followed in 2004 [241] and JET published results in 2005 [242] confirming the major findings of DIII-D - ctr-NBI and recycling control with glow-discharge cleaning, strong pumping, and a careful positioning of the plasma inside the vessel, and, in case of JET, beryllium evaporation. On ASDEX Upgrade, the EHO had $n=1$ toroidal symmetry and m according to the q-value in the transport barrier.

Another promising advanced mode of this kind may be the so called “improved L-mode”, realised first on ASDEX Upgrade in 1994 [243] and later, 2010, rediscovered by Alcator-C-Mod and dubbed “I-mode”²⁴⁴ (improved mode). The first publication of C-mod is entitled: “I-mode: an H-mode energy confinement regime with L-mode particle transport in the Alcator C-Mod” [245]. In a related paper by ASDEX Upgrade, the authors write: “Therefore, these plasmas exhibit an edge transport barrier for

²³⁵ Y. Takase et al., in Proc. 16th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Montreal, 1996 (IAEA, Vienna 1997) Vol. 1, 475.

²³⁶ X. Q. Xu et al., Phys. Plasmas 7 (2000) 1951.

²³⁷ K. H. Burrell et al., Bull. Am. Phys. Soc. 44 (1999) 127.

²³⁸ K. H. Burrell et al., Plasma Phys. Control. Fusion 44 (2002) A253.

²³⁹ K. H. Burrell et al., Bull. Am. Phys. Soc. 59 (2014) 122.

²⁴⁰ W. Suttrop et al., Plasma Phys. Control. Fusion 45 (2003) 1399.

²⁴¹ Y. Sakamoto et al., Plasma Phys. Control. Fusion 46 (2004) A299.

²⁴² W. Suttrop et al., Nuclear Fusion 45 (2005) 721.

²⁴³ F. Ryter et al., Plasma Phys. Control. Fusion 40 (1998) 729.

²⁴⁴ not to be confused with the I-phase.

²⁴⁵ D.G. White et al., Nuclear Fusion 50 (2010) 105005.

heat but L-mode particle transport” [246]. These two nearly identical statements highlight the most promising feature of the I-mode, the reduced particle transport remaining at the level of the L-mode.

The I-mode [247] develops gradually rather in the form of a soft bifurcation. A temperature edge pedestal forms comparable to the one of the H-mode. The density profile at the edge does not change at the L – I transition. Therefore, the edge pressure gradient remains beneath the critical ELM limit of the H-mode. As a consequence, the E_r -field well deepens at the transition to the I-mode but not to the depth of the H-mode. As the shear-flow turbulence suppression criterion is not fully met, a reduced fluctuation level is preserved and GAMs driven by the remaining turbulence are present during the I-mode. As discussed above, in the H-mode the remaining turbulence level is not able to drive any flow which is therefore exclusively neoclassical in its nature.

The important feature of the I-mode is a weakly coherent mode (honoured by the acronym WCM) acting at the edge where otherwise ELMs are located. Like in the other cases, this mode seems to provide the mechanism which allows preferentially particles to escape circumventing the canonical link between energy and particle transport.

The I-mode can exist in a large parameter range and is a candidate for an ITER operational scenario. In course of time, the I-mode can transit and become a regular H-mode. To suppress this tendency, the preferred configuration is normally in reverse fashion with the ion-grad-B drift away from the active X-point. This scheme may be a problem for ITER known for its frugal outfit with auxiliary heating power [248].

Nowadays, research into the I-mode is still on the agenda. The QH-mode may have lost some of its popularity by the fact that ctr-NBI may not be a useful method for ITER²⁴⁹ and that a career of the QH-mode on JET was hampered by the strong efforts of recycling control necessary, a lack of reproducibility [250], and a short-lived nature of this regime, which has also been plagued by intense MHD in the plasma core. DIII-D, however, continued to specifically explore more of the inherent physics behind this regime, the EHO, and the mechanisms to suppress ELMs. Very important for the deeper understanding of the QH-mode and its further improvement was the clarification that ELMs are the consequence of the rising pressure gradient and the induced bootstrap current density at the plasma edge which ultimately destabilise high-n ballooning and low-n peeling/kink modes which couple together to ballooning-peeling modes [251]. The understanding of the stability domain of this combined mode allowed to fully exploit it and thus to further improve the confinement of the QH-mode.

4.3.5 The HDH-mode of W7-AS

W7-AS reported in 2002 shortly before the device was de-commissioned also on a confinement regime without ELMs with H-mode energy and L-mode particle confinement [252]. This regime developed at high density out of L- or H-mode confinement with or without ELMs. Most spectacular was the development out of a quiescent H-phase with strongly increased impurity radiation. Initiating a further density increase by gas puffing gave rise to a sudden self-purification of the plasma shortly

²⁴⁶ F. Ryter et al., Plasma Phys. Control. Fusion 40 (1998) 725.

²⁴⁷ A.E. White et al., Phys. Plasmas 22 (2015) 056109.

²⁴⁸ F. Wagner et al., Plasma Phys. Control. Fusion 52 (2010) 124044.

²⁴⁹ meanwhile, DIII-D has discovered the QH-mode also with co-rotation: K. H. Burrell et al., Proc. 21st Int. Conf. on Fusion Energy 2008 (Geneva, 2008) (Vienna: IAEA) CD-ROM file EX/8-4.

²⁵⁰ W. Suttrop et al., Nuclear Fusion 45 (2005) 721.

²⁵¹ H. R. Wilson et al., Plasma Phys. Control. Fusion 48 (2006) A71.

²⁵² K. McCormick et al., Phys. Rev. Letters 89 (2002) 015001-1.

before a collapse of the discharge. The period following the HDH-transition was without ELMs at low Z_{eff} and impurity radiation. In this very pure high-density phase, beyond the formal Greenwald density limit, the energy confinement time surpassed the standard scaling value by a factor of two. The analysis of the impurity transport yielded a strong reduction of the inward convective flow. This was also manifested by the density profile which was dead-flat up to the separatrix. The critical density for the formation of the HDH-regime increases with heating power up to $2.2 \cdot 10^{20} \text{ m}^{-3}$ at 3 MW absorbed beam power. Under these conditions the divertor was partially detached [2] and plasma exhaust was strongly eased. The HDH-mode is reminiscent of the EDA-mode of C-Mod. Research on W7-X has to show whether the HDH-mode is limited to low collisionality conditions as they prevailed on W7-AS. The physics of the HDH-mode could not be resolved in the remaining experimental time of W7-AS. It was conjectured that the island chain which establishes the edge separatrix is instrumental in screening the external impurity and neutral particle fluxes [253].

5. Internal transport barriers²⁵⁴

In another R&D line of fusion research – making the pulsed tokamak discharge steady-state – external current drive by directed energetic particles or e.m. waves [2] was employed to plasma scenarios displaying a high bootstrap current j_{bst} . As j_{bst} rises with β_p , these scenarios operate generally at lower current and developed surprisingly enhanced confinement in the “proper” radial zone. The bootstrap current density is large at the location of the off-axis pressure gradients leading to broadened current density profiles. Therefore, stability governed by plasma shape, pressure- and q-profiles have to be considered together for these high- β/β_p scenarios. In order to maximally utilise the ohmic current drive for long pulse durations, or, in another scenario, to avoid the early onset of sawteeth in the plasma core, auxiliary heating has to start very early in the discharge. Such scenarios start with a broadened non-equilibrium current profile $j(r)$, which can be even hollow when the ramp rate is higher than the current diffusion time prolonged by early electron heating. Under these circumstances a different set of equilibria develops where the q-profile does not rise monotonically to the edge but forms a minimum with magnetic shear $S=0$ around mid-radius rising both to the edge and to the core giving rise to a radial range of low and even reversed magnetic shear. JET was one of the first to start with early heating in the current ramp-up phase to save magnetic flux in the primary system for longer plateau periods needed for pellet injection as reported by G.L. Schmidt 1988 at the IAEA conference in Nice [255].

There are several arguments in favour of stability and confinement improvement with low or even reversed magnetic shear [256]:

- Microinstabilities like resistive ballooning modes, ITG or trapped electron modes experience less curvature drive and can be stable under such conditions as already shown in 70^{ies} of last century [257].
- Turbulent structures can be separated by a minimum in q with shear $S=0$. The q_{min} radius could act as transport barrier or as trigger to one.
- Rational surfaces as potential sources for turbulence are rarefied in the vicinity of $S=0$. Low shear seems to play the dominant role in the iota dependence of τ_E of low-shear stellarators and has been

²⁵³ Y. Feng et al., Nuclear Fusion 46 (2006) 807.

²⁵⁴ review of this topic: Y. Kamada, Plasma Phys. Control. Fusion 38 (1996) 1173.
R.C. Wolf, Plasma Phys. Control. Fusion 45 (2003) R1.

²⁵⁵ G.L. Schmidt et al., in Proc. 12th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Nice, 1988 (IAEA, Vienna 1989) Vol. 1, 215.

²⁵⁶ C. Kessel et al., Phys. Rev. Letters 72 (1994) 1212.

²⁵⁷ B.B. Kadomtsev and O. P. Pogutse, Sov. Phys. JETP 24, 1172 (1967).

noted decades ago [258].

- The lower poloidal magnetic field leads to larger Shafranov shifts amplifying gradient effects on the bad curvature side and avoiding resonances which drive instabilities.
- Access to second stability with respect to ideal ballooning modes at high pressure gradients in the core region with low global and negative local shear [259].

In the optimisation of these high- β/β_p scenarios confinement and stability governed by plasma shape, pressure- and q-profiles have to be considered together. The need to improve stability and confinement simultaneously is expressed in a new figure-of-merit, $\beta_N H_{98y}$. Normalised β , $\beta_N = \beta a B / I_p$ and H_{98y} is the confinement enhancement factor above the standard value of the H-mode scaling [260].

In a well prepared discharge an “internal transport barrier” (ITB) – a radial zone with steep gradients - can develop spontaneously located about half-way to the edge. An ITB develops like its counterpart, the ETB, the external transport barrier of the H-mode, in a spontaneous step as a threshold process. The transition can be abrupt or slow. The target plasma has to be carefully prepared – low recycling wall conditions and low ohmic starting density. The current ramp-up plays a crucial role to enter the plateau phase with a q-profile with either $q(0)$ close to 1 and an extended low-shear zone or, distinguished by an off-axis minimum, with weak negative shear (“reversed shear”, RS) or strongly negative shear (“enhanced negative shear”, ERS) in the core region. In such a case the core profiles of transport related parameters – density, temperature and rotation – can develop a base point at or close to the minimum in q where the transition threshold is lowest. The strongly reversed shear scenario is more subtle and can lead to steeper ITB pressure gradients. The steep gradient range is limited in radial extent and is called internal transport barrier. Inside the barrier, the profiles are typically flat. Like an H-mode can be triggered by a sawtooth collapse, an ITB can also be initiated by an MHD process in the plasma core. Also rational surfaces could play the role of anchor points.

ITBs in the ion channel and in the density are obtained relatively “easy”. The easiness is measured on the resilience of the electron transport to also form transport barriers. ITBs in T_e , the electron temperature (T_e -IBT), require specific settings for electron heating and current drive by ECH and electron cyclotron (ECCD) or lower hybrid current drive [2]. But for all three state parameters, a strong central source helps to form ITBs – strong ion heating as in the hot-ion mode or strong electron heating for T_e -ITBs [261] or a central particle source with pellet injection to peak the density profile.

The term “internal transport barrier” was coined in the paper by Y. Koide et al. from 1994 entitled “Internal transport barrier on $q=3$ surface and poloidal plasma spin up in JT-60U high- β_p discharges” [262]. In the following year, F. M. Levinton et al., published the paper: “Improved Confinement with Reversed Magnetic Shear in TFTR” [263] submitted May 23rd to Physical Review Letters followed immediately by the paper by E. J. Strait et al. “Enhanced Confinement and Stability in DIII-D Discharges with Reversed Magnetic Shear” [264] submitted June 12th. The title of these papers highlights some of the special features of the equilibria - the reversed magnetic shear, the possible role of resonant surfaces, and the link between stability and confinement. ITBs are established in limiter and divertor plasmas because the edge configuration does not play a critical role. The new regimes have been dubbed “high- β_p mode” in JT-60U, “reversed shear” (RS) or “enhanced reversed shear”

²⁵⁸ R. Brakel and the W7-AS Team, Nuclear Fusion 42 (2002) 903; and references therein

²⁵⁹ J. M. Green and M. S. Chance, Nuclear Fusion 21 (1981) 453.

²⁶⁰ ITER Physics Basis Editors et al., Nucl. Fusion 39 (1999) 2175.

²⁶¹ Z.A. Pietrzyk et al., Phys. Rev. Letters 86 (2001) 1530.

²⁶² Y. Koide et al., Phys. Rev. Letters 72, 1994, 3662.

²⁶³ F. M. Levinton et al., Phys. Rev. Letters 75 (1995) 4417.

²⁶⁴ E. J. Strait et al., Phys. Rev. Letters 75 (1995) 4421.

(ERS) mode –in TFTR [262] and finally “negative central shear” (NSC) mode in DIII-D [163]. The ERS mode excels by stronger negative shear than the RS mode reducing further particle and ion heat transport and even electron transport leading to a very low fluctuation level. Together with current drive high β_p scenarios with ITBs are qualified for steady-state operation. At JET, the term “OS mode” – optimised shear - is used for discharges with flat or reversed core q-profiles where the profile change was initiated by current drive prior to the main heating pulse [265]. In this mode, JET has carried out DT experiments and reached the highest fusion yield with deuterium plasmas. Another example is the lower hybrid enhanced performance (LHEP) regime of TORE SUPRA [266] characterised by a flat or even reversed q-profile in the core and larger magnetic shear in the gradient region. The electron pressure profile is strongly peaked. In DIII-D and TFTR reversed shear was measured for the first time using motional stark effect giving strong support to the interpretation that reversed shear is actually the case and is necessary for these regimes to improve confinement and to reconcile both stability requirements and confinement [267]. Figure 3 shows profiles with ITBs in density, temperatures and safety factor in the plasma core of JT-60 U [271].

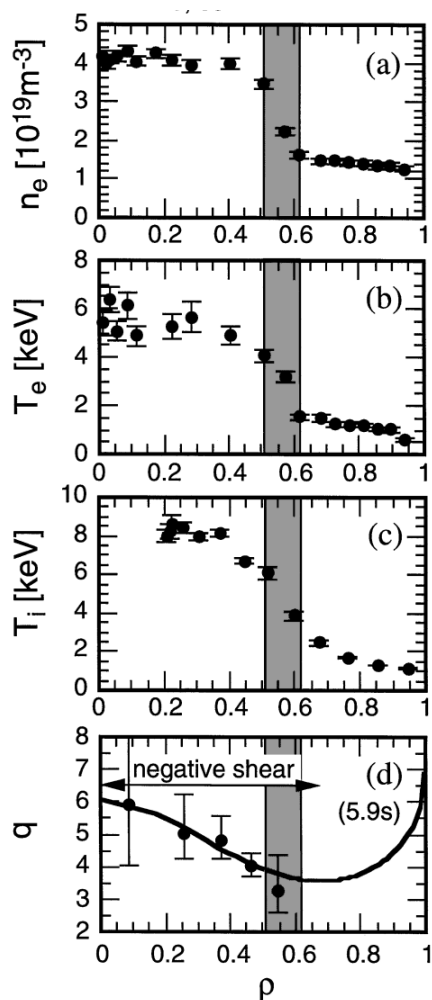


Figure 3. Plotted are density and temperature profiles from JT-60 showing an ITB together with the q-profile showing reversed shear in the core [268].

The ITB scenarios show the critical role of stability to allow steep gradients and to fully utilise the good confinement. Ideal MHD stability theory has shown that β_N increases with internal inductance, l_i . Opposite to the cases discussed above, this scenario requires peaked current density profiles which lead to strong positive magnetic shear. Y. Kamada drew the following conclusion [269]: “These results suggest an improvement of transport both in the negative magnetic shear [37]²⁷⁰ and high positive shear with the near-worst point at the usual current profile in tokamaks.”

Like in the high- β_p , the RS or the ERS scenarios, an operational procedure had to be developed, which allowed the deviation from the canonical current density profile in this case, however, toward a more peaked one. More effective than rapidly reducing the plasma current was the method to rapidly increasing the plasma cross-section during the target plasma formation. In this way, $j(r)$ increases in the core and decreases at the edge, the overall current could be kept large and q_a could stay low.

²⁶⁵ C. Gormezano, JET-Team, in Proc. 16th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Montreal, 1996 (IAEA, Vienna 1997) Vol. 1, 487.

²⁶⁶ Equipe Tore Supra, in Proc. 15th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Seville, 1994 (IAEA, Vienna 1995) Vol. 1, 105.

²⁶⁷ E. J. Strait et al., Phys. Rev. Letters 75 (1995) 4421.

²⁶⁸ T. Fujita et al., Phys. Rev. Letters 78 (1997) 2377 and T. Fujita et al., Phys. Rev. Letters 78 (1997) 4529.

²⁶⁹ Y. Kamada, Plasma Phys. Control. Fusion 38 (1996) 1173–1188.

²⁷⁰ C. Kessel et al., Phys. Rev. Lett. 72 (1994) 1212.

In case of TFTR [271] the minor plasma radius a was first kept small at large aspect ratio; then the plasma was moved inward and in the final step, a was increased typically by a factor of 2. I_i values close to 1.5 were achieved in this way. In case of DIII-D the plasma elongation ϵ was quickly increased to peak $j(r)$ [272]. The density profile was found to peak along with I_i and the toroidal plasma rotation strongly increased.

With an ITB, it is generally the ion pressure gradient which is strongly increased and the ion transport drops – in case of DIII-D to the neo-classical level, in case of TFTR even below it. This surprising aspect has been confirmed by JT-60U [273]. Both papers point out that the pressure gradient length compares with the banana width of thermal ions violating in these cases the ordering of standard neo-classical theory²⁷⁴.

Transport analysis showed that the expected effect of low or reversed magnetic shear on turbulent instabilities - to reduce growth rates and transport - does not fully explain the local transport improvement [275]. The presence of a power threshold to develop an ITB, increasing with magnetic field like in case of ETBs, demonstrated already the existence of a further mechanism based on kinetic effects and not on equilibrium features. As for the H-mode and the ETB, also for ITBs, shear flow decorrelation plays a decisive role to reduce the turbulence level and to improve gradients in a radial range further in. The leading term in the E_r formation can be the pressure gradient whose signature identifies an ITB. Poloidal flow velocities of impurities are observed exceeding the neoclassical impurity flow level [276]. Whereas toroidal flow does not play a major role in ETB formation (apart from the VH-mode) the v_ϕ -term in the radial force balance (equ. 3) can dominate under conditions of strong parallel beam heating as it is the case with the NCS regime in DIII-D. The DIII-D team carried out a crucial experiment to verify the role of shear flow decorrelation acting also in the plasma core. Using an external “brake” the toroidal flow velocity and along with it the radial electric field could be varied and fluctuation level, profiles and confinement responded as expected [277]. A similar experiment had no effect on the status of the H-mode, also in agreement with expectation [278].

The v_ϕ -term in the force balance gives rise to a positive E_r -field with shear. The BDT-criterion (equ. 2) is, however, independent of the sign of the field shear. Also for ITBs like for ETBs a loop process is initiated mediated by the E_r -shear where turbulence is reduced and gradients are steepened. Turbulent electron transport, based on the ETG instability, is less susceptible to $E \times B$ shear flow suppression owing to its smaller scale and larger mode numbers which might explain the more hesitant development of e-ITBs.

The role of $E \times B$ shear flow on turbulence at the location of an ITB has been demonstrated in steps similar to those of the H-mode. The turbulence level is reduced within the ITB [279] and the BDT criterion is fulfilled [280] whereas the instability growth rate γ^{\max} is reduced owing to low or negative

²⁷¹ S. A. Sabbagh et al., Phys. Fluids B3 (1991) 2277.

²⁷² J. R. Ferron et al., Phys. Fluids B5 (1993) 2532

²⁷³ T. Fujita et al., Phys. Rev. Letters 78 (1997) 2377.

²⁷⁴ alternatively, a heat pinch has to be conjectured.

²⁷⁵ P. Zhu et al., Phys. Plasmas 7 (2000) 2898.

²⁷⁶ Y. Koide et al., Phys. Rev. Letters 72, 1994, 3662

²⁷⁷ R. J. La Haye et al., Phys. Plasmas 1 (1994) 373.

²⁷⁸ R.J. La Haye et al., Nuclear Fusion, 33 (1993) 349.

²⁷⁹ K. H. Burrell, Phys. Plasmas 4 (1999) 4418.

²⁸⁰ E. Mazzucato et al., Phys. Rev. Letters 77 (1996) 3145.

L.L. Lao et al., Phys. Plasmas 3 (1996) 1951.

shear. Also the radial correlation length of turbulence is found to be reduced [281]. Of special value is the recognition of the E_r -field shear in TFTR and in DIII-D. In both cases it is large but in case of TFTR [282] it is negative, as conventionally the case with steep ion pressure gradients, whereas in DIII-D [283] it is positive because of a large $v_\phi B_\theta$ contribution to E_r (see equ. 3).

Profiles with ITBs have lost their canonical shapes and do not obey “profile consistency” any longer. Critical onset conditions and marginality conditions leading to profile consistency are irrelevant in radial zones with low turbulence level causing steep gradients. Discharges characterised by an ITB excel by a very high fusion yield and indeed the best values of this parameter were obtained in several devices with improved core confinement [284]. The highest $Q_{DT} \sim 1.05$ (extrapolated, however, from DD operation) has been achieved in JT-60U with reversed shear and an ITB [285].

Also helical systems have reached ITBs based on the quench of turbulent transport. In CHS, ECH led to a T_e -ITB in a radial zone with reduced turbulence level and a corresponding change in the E_r structure [286]. Pellet injection into Heliotron-E led to strongly reduced ion heat transport and, thanks to the profile peaking, to a strongly reduced negative electric field with strong shear [287]. An interesting case has been observed in W7-AS within the transition layer between the electron root in the core and the ion root further out [288]. Within 1 – 2 cm E_r drops by 40 keV. In this case the shearing rate in the transition zone exceeds the instability linear growth rate and an internal transport barrier develops. The development of the ITB shows dithers at the transitional power or electron temperature, respectively, and a hysteresis between creation at high and loss toward low power. This case is another example where the neo-classical ambi-polarity condition tames turbulence.

The two features, ETB and ITB, can be merged in the experiment [289] though ELMs can impede, even prevent the formation of ITBs and the ETB can weaken the flow shear in the plasma core. Nevertheless, the H-mode edges has been combined with the “high- β_p mode” [290], the “PEP mode” [291] and the “NCS mode” [292]. With regard to the two goals of ITER – $Q=10$ in an inductive and $Q=5$ in a steady-state scenario, improved confinement will play a major role. In so-called hybrid scenarios, improved H-modes with ETBs are combined with an extended range of low magnetic shear and $q(0) \sim 1$ in the core [293]. They could help to reach the first goal. So called advanced tokamak (AT) operation²⁹⁴ with strongly improved confinement and stability may qualify for steady-state operation. T.S. Taylor proposes an AT with VH-mode edge and reversed shear core conditions with

²⁸¹ R. Nazikian et al., in Proc. 17th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Yokohama, 1998 (IAEA, Vienna 1999) Vol. 4, 1689.

²⁸² E. J. Synakowski et al., Phys. Rev. Letters 78 (1997) 2972.

²⁸³ K. H. Burrell, Phys. Plasmas 4 (1997) 1499.

²⁸⁴ R.C. Wolf, Plasma Phys. Control. Fusion 45 (2003) R1.

²⁸⁵ Y. Koide et al., Phys. Plasmas 4 (1997) 1623.

²⁸⁶ A. Fujisawa et al., Phys. Rev. Letters 82 (1999) 2669.

²⁸⁷ K. Ida et al., in Proc. 16th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Montreal, 1996 (IAEA, Vienna 1997) Vol. 2, 335.

²⁸⁸ U. Stroth et al., Phys. Rev. Letters 86 (2001) 5910.

²⁸⁹ review of this topic: Y. Kamada, Plasma Phys. Control. Fusion 38 (1996) 1173.

²⁹⁰ Y. Koide et al., Phys. Rev. Letters 72 (1994) 3662.

²⁹¹ B.J.D. Tubbing et al., Nuclear Fusion 31 (1991) 839.

²⁹² E. A. Lazarus et al., Phys. Rev. Letters 77 (1996) 2714.

²⁹³ O. Gruber et al., Nuclear Fusion 49 (2009) 115014.

²⁹⁴ this term was fashionable the 15th IAEA conference in Seville, Spain, 1994.

the core also being in the second stable regime [295]. This confinement and stability scenario has been called second stable core (SSC) - VH-mode - maybe the best fusion research can offer up to 2016.

6. The universal role of shear flow decorrelation²⁹⁶

A carefully MHD analysis of the JET PEP mode [297] – a representative of the peaked density profile confinement category - showed that also in this case the q-profile seems to be reversed. In 1986, C-Mod confirmed the hollow current density profile in the PEP mode using Li-pellets with ablation cloud imaging [298]. Also in the PDP confinement category a strong self-regulating process seems to be at work – the improved confinement leads to stronger gradients which shift the current density to the off-axis bootstrap current maximum giving rise to flat and even reversed q-profiles further fostering this loop process. Specifically, the density gradient is very effective in this process. Within the development of the Supershot characteristics, the density gradually peaks and the ion temperature follows along in radial ranges where the electric field develops shear. The increasing shearing rate reduces ion transport causing χ_i to drop with increasing T_i [299]. The Supershot profiles bootstrap themselves toward a transport equilibrium with excellent core confinement. Toward the edge, the shearing rate loses its effectiveness and ITG L-mode transport with $\chi_i \sim T_i$ prevails. Carefully poloidal flow measurements under balanced beam injection showed that the E_r -field is not simply neo-classical rather seems to contain a turbulent contribution – like we saw it in case of the H-mode.

The density profile peaking with ctr-NBI (see chap. 3.2.4) has been analysed in [300]. The anomalous convective inward velocity stems from the poloidal friction force interacting with the fluctuating electric field. The other ohmic cases with peaked profiles have not been analysed in retrospect in much detail. Nevertheless, GAMs have also been observed in ohmic plasmas [301] and also their interaction with drift-wave turbulence has been observed [302]. Possibly, self-regulating mechanisms set the turbulent level also under these low β conditions.

In summary, the improvement of confinement seems to be based on one primary mechanism which applies to both ETBs and ITBs and plasmas with peaked density profiles, which is shear flow decorrelation of turbulence. For the BDT-criterion (equ. (2)) to become effective, prerequisites seem to be necessary. They seem to differ for ETBs and ITBs. The proximity of the edge separating the electrostatic potential of open and closed field lines and easing the development of non-ambi-polar conditions affects specifically the left hand side of equ. (2) allowing ETBs to form. The low or even reversed magnetic shear conditions in the plasma core (like the high T_i/T_e in the hot-ion mode, increased Z_{eff} in cases with impurity seeding or increased magnetic edge shear) reduce the growth rate of instabilities and affect the right hand side of equ. (2).

The development of ETBs and ITBs can be rather abrupt and a power threshold needs to be overcome in both cases. Dithers or LCOs appear in the H-mode transition as a manifest of the existence of two

²⁹⁵ T.S. Taylor et al., Controlled Fusion and Plasma Physics (Proc. 21st Eur. Conf. Montpellier, 1994), Vol. 18B, Part 1, European Physical Society, Geneva (1994) 403.

²⁹⁶ K. H. Burrell et al., Plasma Phys. Control. Fusion 31 (1989) 1649.

²⁹⁷ M. Hugon et al., Nuclear Fusion 32 (1992) 33.

²⁹⁸ D. T. Garnier et al., in Proc. 16th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Montreal, 1996 (IAEA, Vienna 1997) Vol. 1, 907.

²⁹⁹ D.R. Ernst et al., Phys. Rev. Letters 81 (1998) 2454.

³⁰⁰ A. Fukuyama et al., Plasma Phys. Control. Fusion 36 (1995) A159.

³⁰¹ Y. Hamada et al., Plasma Phys. Control. Fusion 48 (2006) S177.

³⁰² Y. Nagashima et al., Plasma Phys. Control. Fusion 48 (2006) S1.

well separated confinement branches. LCOs are observed in reversed shear discharges where the BDT-criterion is marginally fulfilled but not (yet) under the strong reversed shear conditions of the ERS mode [303].

7. Conclusions

The preoccupation with enhanced confinement regimes created a new understanding of turbulent transport historically dubbed “anomalous transport” because its governing physics eluded rapid clarification. A credible conception has emerged now – gradient driven drift-wave type turbulence develops to a level set by the spatial variation of neo-classical and self-driven plasma flows. Turbulence and flows have to be treated self-consistently. This frame of understanding has the additional beauty that one component is not exclusively restricted to plasma physics but rather unique and encountered also in other fields where sheared flows within neutral fluids regulate turbulence. Examples are flows within the planetary atmosphere e.g. leading to the rings of Jupiter and Saturn, flows in the sun’s convection zone, the polar jet stream in Earth’s atmosphere or oceanographic flows like the Gulf stream [304]. Examples are collected and discussed in [305]. P.H. Diamond et al. write in their 1992 IAEA fusion energy conference paper [306]: “...mean shear amplification is an example of a type of self-organisation process known for a long time in geophysical fluid dynamics (...) and recently encountered in the plasma community...”.

The other feature of the new confinement paradigm is rooted in one of the most basic plasma characteristics as plasmas are composed of light negative and heavy positive charges with strongly different mobilities – the law of ambi-polarity and the related electric field, which ensures transport equilibrium within this medium. In magnetically confined plasmas the ambi-polar electric field causes sheared flows which interact with turbulence and regulate its level.

Some of the essential preconditions to improved confinement regimes are surprisingly identical for tokamaks and stellarators: recycling control and avoiding gas puffing, sufficient heating power to overcome thresholds and peaking of the density profile. ETBs and ITBs develop in both concepts with the addition of neo-classical ion- and electron root physics in helical systems. Recycling control rewards with good confinement when limiters, specifically low-field-side limiters are replaced by a separatrix, graphite first walls by metal ones and gas-puffing by pellet injection. Also the H-mode power threshold can strongly increase with excessive gas puffing [307] or decrease when the edge source is moved into the divertor or to the high-field side [308]. In [309] it has been shown that high-field side fuelling is beneficial because it reduces neutral gas viscosity easing access to the H-mode. The degree of power degradation and the additional degradation toward the density limit suffer from gas puffing. It will be a challenge to maintain recycling control under steady-state conditions when walls are getting saturated. In the future programme, non-inductive scenarios with continuous pellet

³⁰³ E. Mazzucato et al., in Proc. 16th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Montreal, 1996 (IAEA, Vienna 1997) Vol. 1, 913.

³⁰⁴ R. Krishnamurti and L.N. Howard, Proc. Natl. Acad. Sci. USA 78 (1981) 1981.
L. N. Howard and R. Krishnamurti, J. Fluid Mech. 170 (1986)385
B. Galanti and P.L. Sulem, Phys. Fluids A3 (1991) 1978.

³⁰⁵ P. W. Terry Rev. Mod. Physics 72 (2000) 109.

³⁰⁶ P. H. Diamond et al., in Proc. 14th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Würzburg, 1992 (IAEA, Vienna 1993) Vol. 2, 97.

³⁰⁷ W. Köppendörfer et al., in Proc. 15th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Seville, 1994 (IAEA, Vienna 1995) Vol. 1, 241.

³⁰⁸ ASDEX team, Nuclear Fusion 29 (1989) 1959.

³⁰⁹ R. J. Akers et al., Plasma Phys. Control. Fusion 45 (2003) A175.

refuelling have to be cultivated. Gas puffing as the main particle source should be forbidden. Like the other effect from time immemorial, the isotopic effect, recycling control allowing low edge densities during the low- β starting scenario and removing additional momentum losses at the edge is not yet addressed much by theory [310].

Building upon the accumulated knowledge the design of ITER includes a strongly shaped cross-section with an X-point and a divertor and a low-recycling metal wall in agreement with general perception. Shaping will improve stability from which also the confinement will benefit after the formation of ETBs and ITBs. Thanks to the advanced confinement modes, ITER [311] might go beyond its canonical goals of $Q=10$ in the inductive and $Q=5$ in the steady-state scenario [312]. In the first case, hybrid scenarios [313] might allow to push Q , in the second case the benefits of AT scenarios might help to reach or even surpass the goals. But the advanced scenarios are subtle and tend to disruptions. Also ELM suppression, α -particle confinement in case of the high- β_p mode, impurity accumulation in cases with peaked density profiles, and, generally, electron transport need further consideration. At the end, ITER has to identify the best confinement conditions by itself. But guidelines are available from the research done in the past. Reaching the goals could also turn out to be easier than anticipated because the isotopic effect will be beneficial in DT discharges and the tendency of density profile peaking toward lower collisionality [314] could ease access to ITBs together with pellet injection which will be required anyway.

Steady-state operation is the main objective of helical systems. The most advanced device, Wendelstein 7-X, has started operation when this report was written. The W7-X magnetic design promises good stability, a reversed shear configuration built into the vacuum field and the E_r -field effects of a 3-dimensional configuration. Regarding transport, W7-X is optimised guided by neo-classical physics; the overall optimisation results in features which, as we have seen, promise access to confinement regimes with reduced turbulence. The conditions to access the HDH-mode have to be further explored.

B. Kadomtsev and O. P. Pogutse stated [315]: “The question of achieving controlled fusion thus reduces to the possibility of reducing the turbulent diffusion coefficient to a value that is two orders of magnitude smaller than the Bohm value”. Maybe, the conclusion of this paper could be – yes, mission successfully completed. In the radial zones of ETBs and ITBs, turbulent confinement has been strongly reduced, the ion transport can be at the neo-classical level for all radii [316] and the local confinement is effectively governed by the stability of global modes at gradients which could even violate the assumptions of conventional neo-classical transport theory. Hardly more can be asked for.

³¹⁰ P. H. Diamond et al., Phys. Fluids, 30 (1987) 3724.

B. A. Carreras et al., Phys. Plasmas 1 (1996) 4106.

³¹¹ ITER Physics Basis, Nuclear Fusion 39 (1999) 2137.

³¹² A.C.C Sips et al., Plasma Phys. Control. Fusion 47 (2005) A19.

³¹³ O. Gruber et al., Nuclear Fusion 49 (2009) 115014.

³¹⁴ C. Angioni et al., Phys. Rev. Letters 90 (2003) 205003.

³¹⁵ Reviews of Plasma Physics, M.A. Leontovich, Ed. New York: Consultants Bureau, 1970, Vol. 5, p. 249.

³¹⁶ E. A. Lazarus et al., Phys. Rev. Letters 77 (1996) 2714.