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Advancing the understanding of plasma transport in mid-size stellarators

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Abstract
The tokamak and the stellarator are the two main candidate concepts for magnetically confining fusion plasmas. The flexibility of the mid-size stellarator devices together with their unique diagnostic capabilities make them ideally suited to study the relation between magnetic topology, electric fields and transport. This paper addresses advances in the understanding of plasma transport in mid-size stellarators with an emphasis on the physics of flows, transport control, impurity and particle transport and fast particles. The results described here emphasize an improved physics understanding of phenomena in stellarators that complements the empirical approach. Experiments in mid-size stellarators support the development of advanced plasma scenarios in Wendelstein 7-X (W7-X) and, in concert with better physics understanding in tokamaks, may ultimately lead to an advance in the prediction of burning plasma behaviour.

Keywords: plasmas, stellarators, fusion

(Some figures may appear in colour only in the online journal)

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1. Introduction

The roadmap to a feasible fusion reactor based on the tokamak line is already established, while alternate concepts exist which may allow for further improvement. In this respect, the stellarator concept offers a route to a fusion power plant with unique capabilities: steady state operation, absence of plasma disruptions and high density operation.

Like tokamaks, stellarators are toroidal confining devices but they show two fundamental differences: the confining magnetic field is generated by external coils and the lack of toroidal symmetry. The history of tokamaks shows that from the original concept, solutions have converged into a given range of configurations. However, stellarator diversity has been amplified with the development of improved concepts: quasi-toroidal symmetry [1], quasi-helical symmetry [2] and quasi-isodynamic (W7-X) [3]. The successful start of the scientific exploitation of W7X [4] is the first step towards bringing the stellarator to maturity as foreseen in the European Union roadmap.

This work is devoted to discuss the present role of mid-size stellarators in the understanding of basic physical processes in fusion devices, with emphasis on the physics of flows, transport control, impurity and particle transport, fast particles and synergies between tokamaks and stellarators.

2. Configuration optimization

When the magnetic field strength $|B|$ is symmetric in magnetic coordinates (so-called quasi-symmetry), guiding-centre orbits and neoclassical confinement properties are equivalent to those in a tokamak. Within the family of optimized stellarators the quasi-isodynamic W7-X design is based on the minimization of all internal plasma current (i.e. Pfirsch–Schlüter and bootstrap currents). Pioneering calculations showed that such magnetic fields can indeed be realized in practice [3].

Experiments in the helically symmetric experiment (HSX) have shown the effectiveness of quasi-symmetry regarding improved neoclassical confinement to the extent

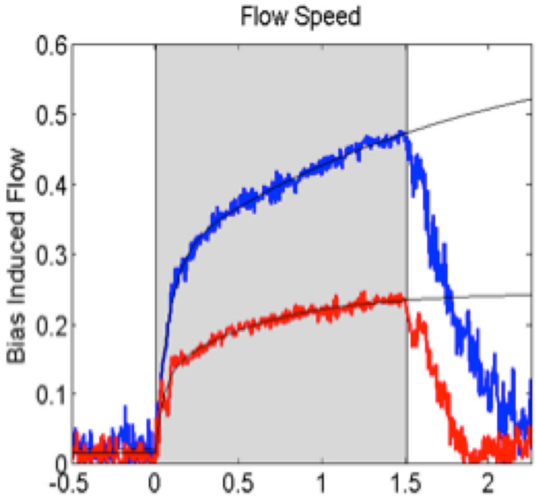


Figure 1. HSX has direction of symmetry in $|B|$, hence a direction of minimal flow damping: blue (QHS), red (mirror) [6].

that turbulent transport dominates over the entire plasma region [5]. Experiments have demonstrated the reduction in parallel viscous damping (figure 1) [6] and that plasma flows follow the direction of quasi-symmetry [7].

Fundamental to the understanding of transport and stability in three-dimensional (3D) stellarators is an accurate method of reconstructing the plasma equilibrium, similar to what is routinely done on tokamaks. Using the V3FIT code [8], it has been demonstrated that the Pfirsch–Schlüter current in HSX is helical because of the absence of toroidal curvature and reduced in magnitude compared to the comparable tokamak [9]. Critical to the proper operation of the island divertor in W7-X is control of the edge rotational transform as the bootstrap current evolves. On HSX 3D equilibrium reconstruction was used to obtain the bootstrap current profile and to demonstrate the critical role of the radial electric field on that profile [10]. Finally, it was demonstrated that optimization of the position of magnetic diagnostics used to perform the reconstruction can reduce the uncertainty in the plasma pressure and current profiles [11].

3. Control of transport

3.1. Zonal flow physics: Diagnostic development as trigger of new physics

With the advent of neoclassically optimized stellarators, optimizing stellarators for turbulent transport is a key next step [12]. Stellarator devices have pioneered the detection of long-range correlations, consistent with the theory of zonal flows i.e. stable modes that are driven by turbulence and regulate turbulent transport [13, 14], of interest in astrophysics, atmospheric dynamics and fusion plasmas.

Physics is an experimental science where theories should be confronted with experimental results. This validation process requires the development of plasma diagnostics to show that a new model faithfully represent physics reality, including quantitative assessments of discrepancies between theoretical and experimental results. From this perspective the direct experimental characterization of zonal flows (ZFs) is a great challenge for experimentalists.

The first experimental evidence of amplification in long-range correlations (as a proxy of ZFs) during the development of core transport barriers was reported in the CHS stellarator [15]. Those results were obtained using a unique experimental set-up employing two heavy ion beam (HIBP) systems. Later experiments performed in TJ-II, HSX and TJ-K stellarators, using dual edge probes as well as dual HIBP diagnostics, have shown that long-range correlations in potential fluctuations are amplified either by externally imposed radial electric fields [16–18] or when approaching the L-H confinement edge transition [19, 20].

A unique experimental set-up in the TJ-K torsatron, based on 128 Langmuir probes, has allowed to measure simultaneously at different toroidal and poloidal positions ZF activity, turbulent transport and Reynolds stress (RS) driven flows (figure 2). It has been shown that ZF and net turbulent transport establish a limit cycle, with minimum transport reached at maximum ZF amplitude [14]. In wavenumber space, ZFs were found to tap energy non-locally from drift-wave turbulence, which corresponds to vortex thinning as observed in 2D neutral fluids. Furthermore, the detailed spatial dependence of turbulent transport is found to be governed by the geometry dependence (including both normal and geodesic curvature) of linear growth rates of drift waves [21]. First direct experimental evidence of strong poloidal RS asymmetry [22] pointed out curvature dependent zonal-flow drive (figure 2). Poloidally, the RS is distributed asymmetrically in the same way as turbulent transport. Asymmetric RS flow drive was also observed on HSX [23]. Thus, care should be taken to prevent a misleading interpretation of local RS measurements [24].

Those findings illustrate how unique diagnostic capabilities implemented in medium size devices make them ideal plasma physics experiments for deeper understanding of ZF dynamics and advanced control of turbulent transport.

3.2. Radial electric fields with multiple radial scales

The ambipolarity condition (i.e. the equality of ion and electron fluxes) determining the radial neoclassical electric field has two stable roots in stellarators: the ion root with typically negative E_r, usually achieved in high density plasmas, and the electron root with positive E_r, that is typically realized when electrons are subject to strong heating. It is the neoclassical transport that determines the radial electric field on long (tens of gyroradius) length scales [25, 26], whereas turbulent mechanisms (e.g. ZFs) can control short (few gyroradius) radial length scales. Then, an important question is to determine the possible interplay between long (neoclassical) and short (anomalous) E_r radial electric fields.

The influence of long-scale length radial electric field components on zonal flow-like structures has been recently reported in the TJ-II stellarator [27]. The calculated $E_r \times B$ shearing rate corresponding to the short scale length structures of the radial electric field may be sufficient to regulate

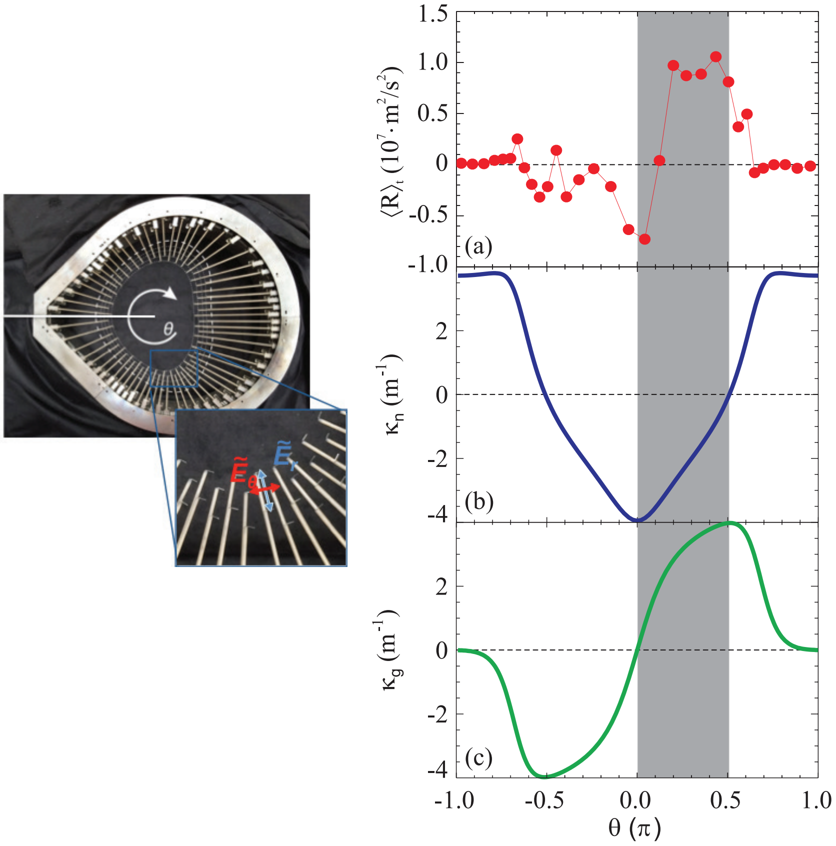


Figure 2. Poloidal Reynolds stress asymmetry in TJ-K. Reused with permission from [22].

turbulence. Interestingly, direct observation of fine scale structures in radial electric fields have been also reported in the JET tokamak consistent with stationary zonal flows [28].

In addition, the dual role of low-order rational surfaces as both damping [29] and drive mechanism of steady-state [30, 31] and fluctuating [19] $E_r \times B$ flows has been identified; thus magnetic topology is an important regulator of radial electric fields, MHD activity and transport levels [32]. In stellarators (e.g. W7-X) islands are basic for divertor configurations [33].

The mechanisms underlying the observed interplay between neoclassical radial electric fields and the amplification of low frequency zonal flow-like structures are at present under investigation, considering (a) that sheared electric fields are efficient turbulence symmetry-breaking mechanism, amplifying the Reynolds stress drive of zonal flows, (b) that radial electric fields give rise to $E_r \times B$ drifts that prevent locally trapped particle orbits from drifting radially, reducing the effective damping of zonal flows. Actually, the amplification of low frequency ZF structures in plasmas with reduced neoclassical viscosity has been confirmed by experimental observations in TJ-II [34].

The development of radial electric fields with multiple radial scales involving both neoclassical and anomalous mechanisms would have direct implication in the physics understanding of transport in fusion plasmas. Further experiments are needed to test the reproducibility, as the basis of the scientific method, of TJ-II and JET findings and to determine in which conditions long or/and short scale E_r structures play a key role in the transition to improved confinement regimes.

3.3. Turbulence optimization

Trapped electron modes (TEMs) are important micro-instabilities to understand transport in fusion plasmas that are sensitive to the overlap of regions of trapped electrons and bad curvature. In W7-X the magnetic field increases in the transition areas between the five field periods; then, trapped particles oscillate between regions of high magnetic field resulting in poloidal rotation but no (or reduced) radial movement. Due to the method in which different stellarators have been optimized, the overlapping between trapped electron and bad curvature regions is minimized in W7-X to stabilize TEMs but not in TJ-II or HSX stellarators. Indeed, gyrokinetic calculations indicate lower growth rates in W7-X than in HSX [35, 36]. However, nonlinear calculations show that the turbulent heat flux levels are only slightly reduced in TEM optimised configurations compared to non-optimized ones [35], possibly hinting at the critical role of zonal flows in the saturation mechanism.

Measurements of heat flux in HSX show good agreement with nonlinear gyrokinetic calculations [37], concluding that TEM, primarily driven by density gradient, is the dominant long-wavelength micro-turbulence instability across most of the plasmas (figure 3). It is an open question as to what determines the nonlinear saturation in TEM turbulence and

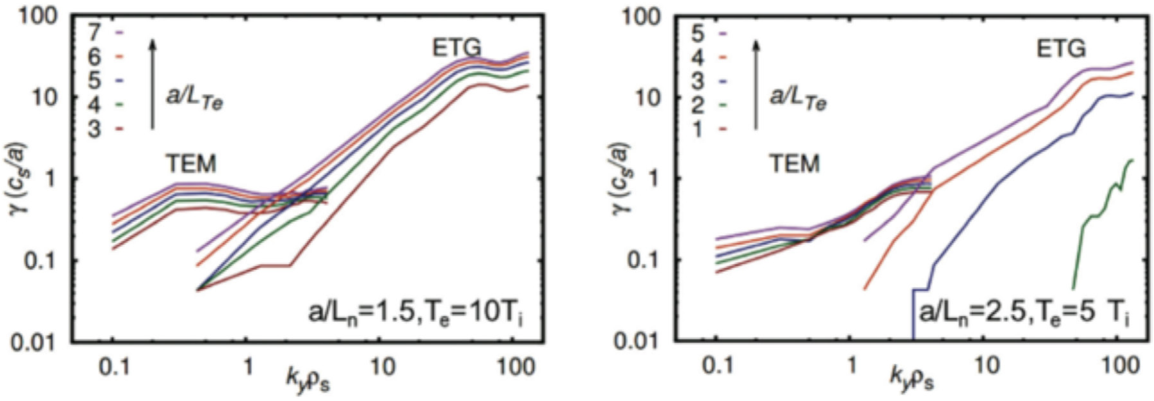


Figure 3. Linear growth rates of TEM and ETG modes in HSX [37], showing that TEM is only weakly dependent on the temperature gradient and is primarily driven by the density gradient. Reprinted with permission from [37] Copyright (2015) AIP Publishing.

how optimization of the 3D boundary may affect turbulent transport.

4. Impurity and particle control

4.1. Searching for mechanisms for impurity control

Particle and impurity transport are usually described empirically in terms of diffusive and convective terms driven by neoclassical and turbulence mechanisms. In the framework of neoclassical mechanisms in tokamaks, the main ion density gradient (inwards) and the ion temperature gradient (outwards at low collisionality, otherwise known as temperature screening) are responsible for opposite convective fluxes. In non-axisymmetric devices the sign of the radial electric field is expected to play a dominant role in the convection of impurities. Thus, by standard neoclassical theory, high inward radial electric fields are foreseen to enhance inward impurity convection in stellarators. As a consequence high density (ion root operation) shows a tendency for impurity accumulation [38]. Interestingly, efficient impurity control has been achieved in non-axisymmetric plasma regimes with radially inwards radial electric field in high-density H-mode plasmas in the W7-AS stellarator [39] and in the so call impurity hole regime in the LHD helical device [40]. In both cases the underlying mechanisms remain unknown. Those results show that, indeed it is possible the simultaneous achievement of improved energy confinement with low impurity accumulation which is a necessary condition for the development of fusion reactor relevant scenarios.

Significant progress has been reported regarding the physics understanding of empirical actuators, like ECRH/ICRH core heating, to avoid impurity accumulation, including the following mechanisms:

- A reduction of the background density gradient, leading to a reduction of the inward (neoclassical) convection of impurities in tokamaks and stellarators.
- An increase of turbulent level both tokamaks [41] and stellarators [42]

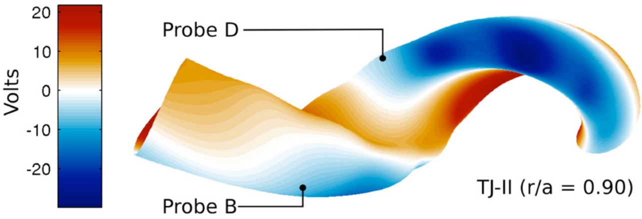


Figure 4. Observation of plasma potential asymmetries in the TJ-II stellarator. Reproduced from [44] with permission of the IAEA.

- The amplification of core temperature screening, which would be relevant in core α-heating regimes in tokamaks.
- Modification in the neoclassical radial electric fields in stellarators.
- The development of core plasma potential flux surface asymmetries which due to its 3D structure is expected to be stronger in stellarators than in tokamaks.

It has been predicted that impurity accumulation is affected by 3D asymmetries [43]. Direct experimental observations of electrostatic potential variations within the same magnetic flux surfaces have been reported both in electron and ion root regimes in the TJ-II stellarator [44, 45]. Significant asymmetries are observed in electron-root wave-heated plasmas, which are reduced in ion-root beam-heated conditions and when the electron temperature decreases. The order of magnitude (in the order of tens of volts) as well as the observed dependencies on the electric field root are well reproduced by neoclassical Monte Carlo calculations (figure 4), thus improving confidence in impurity transport predictions. More recently, we have investigated the simultaneous matching of potential profiles and the amplitude of potential modulation induced by biasing in ion-root plasma regimes, concluding that plasma potential asymmetries are ubiquitous in the TJ-II stellarator. It remains an open question how these regimes extrapolate to configurations with reduced neoclassical transport and to plasmas with higher temperatures and lower collisionality.

The unique capabilities of the dual HIBP system allows the investigation of multi-scale mechanisms to be expanded from the plasma edge to the plasma core in the TJ-II stellarator. Experiments with combined NBI and ECR heating have shown direct experimental evidence of the influence of ECRH on turbulent mechanisms, increasing both the level of fluctuation and the amplitude of long-range-correlations (LRC) as proxy of ZFs for potential fluctuations but not for density and poloidal magnetic fluctuations as well as affecting neoclassical radial electric fields. Whereas ECRH influences the level of fluctuations in a wide range of plasma densities, ECRH induced reversal of the neoclassical radial electric field has been observed only in low-density plasmas [42].

4.2. Core fuelling physics

Core plasma fuelling is a central element for the development of credible steady-state scenarios [46]. In stellarators the temperature gradient causes outward neoclassical particle flux and thus tends to create a hollow density profile. As a consequence central particle fuelling would be needed in a reactor. Core plasma fuelling experiments, using pellets in the TJ-II stellarator, have shown that the radial redistribution of particles can be understood qualitatively from neoclassical predictions. In particular, a density peaking due to ablation is initially observed outside the core with the peaking moving inwards. This phenomenon, if extensible to other helical devices, would mean that pellets that do not reach the magnetic axis may still be able to mitigate core depletion [47, 48].

4.3. Transport in plasma boundary region

Plasma edges in stellarators can be quite different than edges in tokamaks. In particular, the long connection lengths in stellarators means that cross-field transport can compete with parallel transport along open field lines. In addition, friction due to counter-streaming flows in stellarators may inhibit access to high recycling regimes. 3D codes such as EMC3-EIRENE [49] that are used to model divertor and edge structures in stellarators and tokamaks need verification and validation. Extensive 2D mapping of plasma edge parameters in HSX showed evidence of counter-streaming flows, a low diffusion coefficient in the scrape-off layer region and the importance of considering edge electric fields in understand transport [50].

The electron density of coherent turbulent structures (blobs) has been measured using the helium line ratio technique at the plasma edge of the TJ-II stellarator [51]. Turbulent plasma density structures have been compared with the raw helium emission structures related to both density and neutral fluctuations. The impact of neutral fluctuations on the observed turbulent structures, an almost fully unexplored area of research, is under investigation [52] with indications that thermal neutrals could react to low frequency plasma fluctuations.

Clarifying whether the SOL width is dominated by local effects at the SOL region or/and by anomalous transport driven in the plasma edge is a relevant question. The unique control of edge radial electric fields in stellarators has allowed concluding that SOL profiles are coupled with edge plasma parameters. Consequently optimizing SOL power exhaust requires considering transport in the edge region [53].

5. Fast particle dynamics

Alpha-particle driven Alfvénic instabilities constitute a source of major uncertainty for predicting alpha-particle transport, alpha heating profile, and He ash accumulation in burning plasmas. Moreover, Alfvén Eigenmodes (AEs) can have a strong influence on the confinement of fast ions, thus making NBI heating less efficient. The HIBP system in operation in the TJ-II stellarator has provided direct measurements of transport induced by AEs (figure 5). It is found that the AEs contribution to the frequency resolved turbulent particle transport constitutes a significant fraction of the total flux [54]. Interestingly although most of the AEs contribute to outwards $E \times B$ flux some modes produce inward flux. This is an important open area of research in view of the plasma performance of stellarator/tokamak reactor devices.

The observed mitigation effect of ECRH on NBI beam-driven AEs first reported in DIII-D [55] and later in TJ-II [56] has opened an attractive avenue for a possible control of the AEs though the physics behind this effect is yet to be understood. Supporting the physics basis for controlling fast particles, experiments in TJ-II have shown that ECRH power changes the continuous character of the Alfvén Eigenmodes (AEs) triggering frequency chirping. The influence of magnetic topology (magnetic islands, well and rotational transform) on AEs has also been reported [57–59].

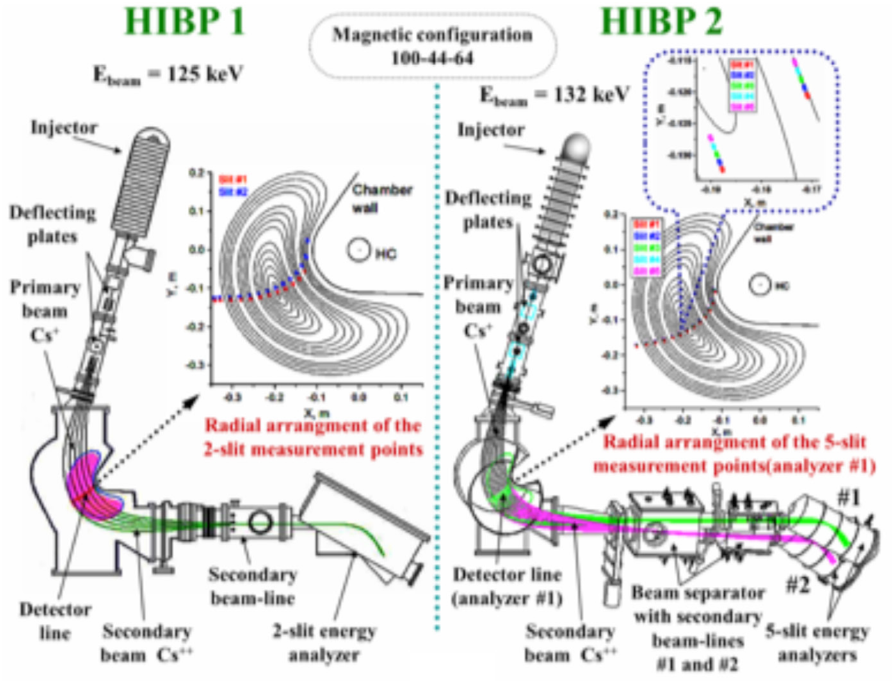
6. Synergies between stellarators and tokamak

Stellarators have both advantages (e.g. intrinsic steady-state operation and disruption-free operation) and disadvantages (technical complexity) compared with tokamaks. From the perspective of plasma physics, synergies between stellarators and the main-line tokamak seem particularly meaningful to address fundamental open questions such as: are there different paths to reach the L-H transition? Why is there decoupling between particle and energy transport channels at the transition to improved confinement regimes? Why does ion mass affect confinement?

6.1. Are there different paths to reach the L-H transition?

While the ion pressure gradient plays an important role in the development of the H-mode in tokamaks [66], in stellarators the ratio of the electric field to the diamagnetic contribution can be larger than one in the H-mode (e.g. W7-AS [60]). Also, long-range-correlations, as a proxy of ZFs, have been observed in the proximity of the L-H transition (e.g. TJ-II [19]). Interestingly strong decoupling between density and potential fluctuations has been reported in the proximity of the L-H transition as fingerprint of ZFs (e.g. TJ-II) [20].

It is concluded that (possibly) there are different paths to reach the L-H transition with impact on the conditions (i.e. power / density threshold) to access the H-mode (figure 6). Experiments are in progress to characterize simultaneously the role of edge magnetic topology in the dynamics of



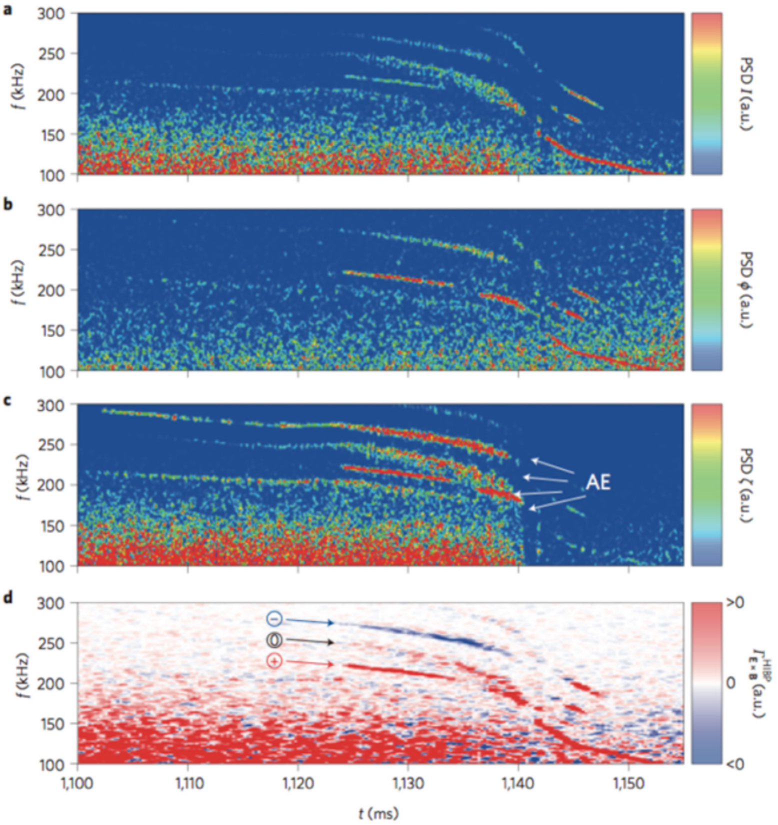


Figure 5. Observation of AEs in the TJ-II stellarator and their influence on turbulent driven transport: ((a)/(b)/(c)) time evolution of the power spectral densities (PSD) measured at mid-radius for total secondary beam current (a), plasma potential (b) toroidal shift (c). The frequency resolved turbulent particle flux shows outward (red/(d)) and inward fluxes (blue/(d)) [54].

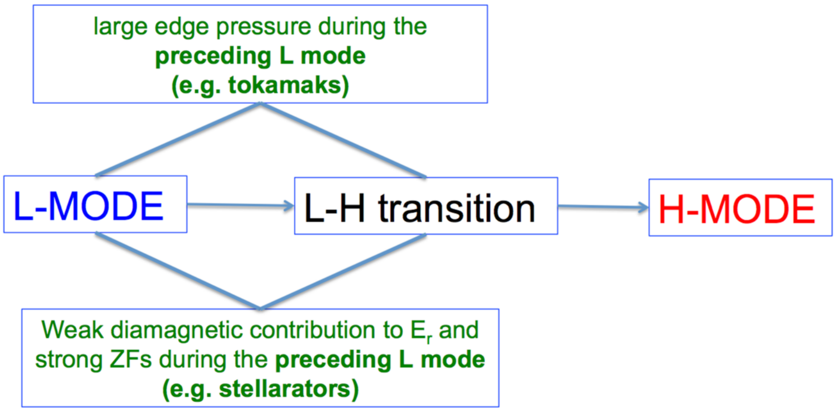


Figure 6. Different routes to reach the L-H transition based on E_r sustained by pressure gradients or ZFs (see section 6).

Table 1. Approaches to investigate and understand ion mass dependences of confinement and transport in tokamaks and stellarators.

Isotope effect: transport and L-H transition	Approach and validation (tokamaks versus stellarators)
Emprical actuators	**Key empirical question**: What are the optimum configuration and plasma conditions for achieving minimum L-H power threshold in the ITER non-nuclear/nuclear phases?
Ion mass (H/D/He)	ITPA scaling laws
Magnetic configuration	Tokamak versus Stellarators, RMPs, *X*-point location
Perturbative effects	e.g. MHD effects
Towards basic understanding	**Role of ion mass on turbulence**: Gyro-Bohm-like scaling in tokamaks [64] and stellarators [65] **Transport**: Ion versus electron transport [66] **Interplay between neoclassical and anomalous mechanisms**: Role of neoclassical E_r and interplay with short radial scale E_r in tokamaks [28] and stellarators [16–18, 27]. **Stability**: Pedestal stability can be affected via a relative shift of temperature and density profiles [67] and role of Z_{eff} [68] **Role of ion mass on Zonal Flow (ZF) and GAMs**: Amplitude of large-scale flows versus ion mass in tokamaks [45, 69, 70] and stellarators [65, 71]. GK simulations [72, 73] **Role of atomic physics**: Boundary conditions (ionization/CX) [52, 74]

pressure gradients and ZFs during the L-H transition in mid-size stellarators.

6.2. Why is there decoupling between particle and energy transport channels at the transition to improved confinement regimes?

Physics behind uncoupled transport channels is a relevant open question for understanding both ELM control techniques (e.g. using RMP) as part of the ITER base-line scenario and the development of plasma scenarios without ELMs (e.g. I-mode). Interestingly, uncoupled transport channels has been also reported in stellarators / heliotrons (e.g. TJ-II [61] and LHD [62]).

Transport channel decoupling could be driven by any mechanism that leads to a modification of the cross-phase between density and temperature fluctuations caused by changing driving conditions [63]. Then, TEM stability (a key element of W7-X optimization strategy) would have a direct impact on particle / energy decoupling mechanisms. Joint actions including modelling and experimental validation in tokamaks and stellarators are in progress to unravel the basic mechanisms allowing a decoupling between particle and energy transport channels exploring e.g. role of the phase relation between density and temperature fluctuations and ZFs.

6.3. Why does ion mass affect confinement?

Two different approaches have been explored to investigate and understand ion mass dependences of confinement and transport:

(1) An engineering approach i.e. use of empirical control parameters like ion mass and magnetic configuration to get the optimum plasma conditions for achieving the minimum L-H power threshold in ITER and confinement optimization;
(2) A basic physics approach i.e. basic understanding of underlying mechanisms including: role of ion mass on turbulence (Gyro-Bohm-like scaling), role of ion and electron transport channels, interplay between long (neoclassical) and short scale (turbulent) radial electric fields, stability and role of plasma profiles and Z_{eff}, influence of ion mass on zonal flows and GAMs and role of atomic physics mechanisms. Studies in tokamaks and stellarators have provided experimental evidence for the importance

of multi-scale physics to unravel the impact of the isotope effect on transport (see table 1).

Thus, comparative studies in tokamaks and stellarators should be promoted to complement capabilities in different areas and to provide a bridge between experimental demonstration and basic understanding.

7. Conclusions

The flexibility of mid-size stellarator devices together with their unique diagnostic capabilities make them ideally suited to study the relation between magnetic topology, electric fields and transport. This paper has addressed advances in the understanding of plasma transport in mid-size stellarators with the following highlights:

1. Zonal flow physics: identifying the importance of poloidal asymmetries in the turbulent drive of ZFs and the role of neoclassical radial electric fields to control the dynamics of ZFs resulting in the development of both long (neoclassical) and short (due to ZFs) radial electric field scales.
2. Turbulence optimization: understanding how to optimize the magnetic geometry by 3D shaping of the plasma boundary to reduce TEM transport and investigating the possible role of zonal flows in determining the nonlinear saturation.
3. Impurity and particle control: identifying plasma potential asymmetries on magnetic flux surfaces.
4. Fast particle dynamics: investigating the role of AEs on turbulent driven transport and the role of ECRH and magnetic topology as AEs control tool.
5. Synergies between tokamaks and stellarators: addressing the existence of possible multiple paths to reach the H-mode, the physics of decoupling between different transport channels, the importance of multi-scale mechanisms on the isotope mass effect and the role of the connection length in varying the essential physics in the plasma edge region and access to high recycling regimes.

Those findings are supporting the development of advanced plasma scenarios in W7-X and complementing the empirical approach to achieve fusion relevant conditions with physics understanding to predict burning plasma behaviour.

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