Effect of Rotational Transform and Magnetic Shear on Confinement of Stellarators

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This work surveys the main results concerning the effects of the rotational transform, its low order rational values and its shear on the confining properties of low shear devices. It is meant to promote further studies aimed at clarifying their role in future, reactor grade, devices. 1-D transport studies are encouraged as the effects of rotational transform on confinement appear to be of local nature. Low order rational values of the rotational transform are associated with both degraded and improved confinement, being the magnetic shear a plausible cause for the difference. Very small shear values are enough to avoid deletereous effects of the low order rationals in high rotational transform discharges, but further experiments are needed to elucidate whether there is a threshold shear that depends on the rotational transform itself.

Keywords: stellarator, heliotron, rotational transform, magnetic shear, confinement

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1. Introduction

The fact that the confining field in stellarators is largely independent of the plasma itself provides an extraordinary freedom of design and is the reason behind the variety of configurations existing or under construction [1]. A significant degree of freedom is the capability of choosing different values and profiles of rotational transform, $\iota\!\!\!-= \iota/2\pi$. Historically, two approaches have been followed to prevent the expected confinement deterioration due to the presence of low order resonances. The first one is to design machines with very flat profiles (extremely low magnetic shear, $\hat{s}$), trying to avoid resonances (for example, the Wendelstein family [2, 3], TJ-II [4], HSX [5], Heliotron-J [6]). W7-X, the large stellarator appearing in the horizon follows the low shear approach and its design has been optimized to have a weak dependence of $\iota\!\!\!-$ on the plasma pressure. The second approach is to look for strongly varying rotational transform profiles that do not avoid the resonances but force the islands to shrink and prevent them to overlap (for example, Heliotron-E [7], L2 [8], ATF [9], CHS [10], LHD [11]).

After those experiments rotational transform and magnetic shear remain as two important issues whose role must be considered in future designs of candidates for a stellarator reactor. The extensive inter-machine 0-D global scaling studies performed to date do not yield a clear picture about the role of $\iota\!\!\!-$ on confinement, as will be discussed later. Additional 1-D information contained in the temperature and density profiles should be considered as well. Local transport analysis can provide valuable information on the role played by the resonances and help in understanding the influence of rotational transform on confinement. This work points in this direction, within the framework of the International Stellarator/Heliotron Confinement DataBase (ISHCDB) under auspices of the IEA Implementing Agreement for Cooperation in the Development of the Stellarator Concept [12]. On the need to clarify the true role of rotational transform and shear in these confinement devices, it is advised searching for appropri-

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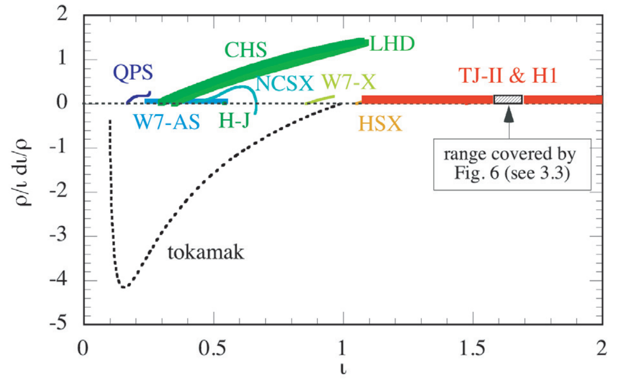

Fig. 1 Range covered by the main operating stellarators in a (ι, $\hat{s}$) parameter space. The tokamak range is also shown for comparison.

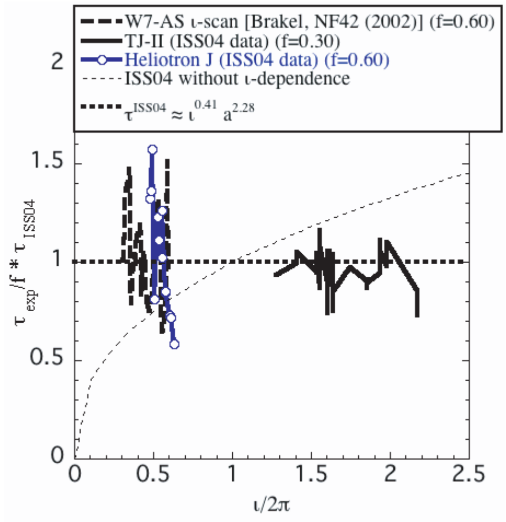

Fig. 2 Comparison of the dependence of renormalised confinement times on ι, for data subsets of W7-AS, TJ-II and Heliotron J.

ate figures of merit in the (ι, $\hat{s}$) parameter space. Figure 1 shows the range covered by the main operating stellarators in (ι, $\hat{s}$). The tokamak range is also shown for comparison. As a first step, it has been found convenient starting with a survey based only on low shear machines, which should help in deciding further steps where large shear devices must be included.

A survey of the results obtained so far on the influence of rotational transform value on global confinement is presented in section 2. The effect of low order resonances on confinement is discussed in section 3. The role of magnetic shear is presented in section 4. The work is concluded with a brief summary in section 5.

2. Dependence of Global Confinement on the Rotational Transform Value

Early tokamak studies predicted that high rotational transform values are favourable for confinement, with exponent 0.4 [13]. In stellarators, the Wendelstein stellarator family was the first to publish experimental results on the confinement dependence on ι owing to the capability of their devices to perform ι scans. They reported a general improvement (energy confinement time and electron heat diffusivity) at higher rotational transform values provided that distinct optimum confinement windows close to low order resonances (1/3 and 1/2) were chosen [14, 15].

ISS95, the first extensive stellarator study based on international collaboration compiled a database from the main devices at that time and deduced an intermachine scaling law, which predicted an improvement of global confinement with increasing ι [16]. However, the fact that an offset between the shear-less machines and the heliotron/torsatrons appeared in the unified scaling required the use of an "ad-hoc" parameter to arrive at a unified expression. This so-called "parameter *s*" accounted for the difference in confinement between stellarators with and without shear.

The individual results from the TJ-II flexible heliac showed again the beneficial effect of ι on the global energy confinement and supported the W7-AS finding in a wider range ($1.2 < \iota < 2.2$) [17].

For the ISS04 revision of ISS95, new devices entered the confinement database: LHD, TJ-II, Heliotron-J and HSX. Particularly important was the contribution from LHD, the largest device, which extended the parameter regime to substantially lower values of normalized collisionality and ion gyro radius, much closer to reactor regimes than those of the ISS95 devices [18]. Besides, W7-AS had discovered significant high confinement regimes with divertor operation. Thus, a new larger database was compiled including these new results. ISS04, the new scaling expression, was derived from a restricted set from the full database. The dependence of global confinement on ι deduced from ISS04 is again positive, with exponent 0.4, in line with ISS95, but again a caveat questions this result. In ISS04, the use of the old "parameter *s*" was not sufficient to arrive at a unified scaling and a new empirical configuration-descriptive renormalization factor, f_{ren}, derived for each configuration subgroup, was used [19, 20]. This factor was related to specific properties of the helical field structure of each device; it appears to be correlated, for instance, with the corresponding effective helical ripple, plateau factor and elongation. Taking into account the corresponding configuration factors, the ι-dependence of different machines can be compared.

Figure 2 shows, for example, the renormalized confinement times of data subsets from the low shear devices W7-AS, TJ-II and Heliotron-J [19, 21]. It can be seen that the intermachine comparison is consistent as regards the ι-dependence (the data clouds are positioned over the ISS04 horizontal line) but there is a saw-like fine structure within each data subset, which is a typical feature of low shear stellarators. It is related to the effect of low order rationals and influenced also by the reduction of plasma radius due to the appearance of natural islands at the boundary [16, 22].

The conclusion of this summary is that the search for physical mechanisms behind the configuration factors suggested by the ISS04 study requires a step beyond, considering detailed profile information as well as neoclassical and turbulent transport effects. Local transport analysis appears as an essential tool in this process to understand which are the plasma regions where the confinement is improved and to go deeper in the physics involved in the transport reduction.

3. Effect of Low Order Resonances on Confinement

Both low and high shear approaches face challenges regarding the effect of low order resonances. Examples are i) keeping the configuration free of resonances at high β in low shear devices or ii) maintaining the divertor capabilities in high shear machines. In any case, there are some open questions that need to be addressed:

- Is there a threshold for the magnetic shear over which low order resonances lose their detrimental character? Does this threshold depend on the value of the rotational transform itself?
- What is the effect of resonances when the shear is above this threshold?
- Is the sign of the shear important, or is only its magnitude what matters?

The logic behind this type of questions is clear: Provided that low order resonances do not deteriorate confinement anymore in the presence of enough (perhaps very low) magnetic shear -or, even more, if they can act as regulators of the local transport in both senses (enhance-decrease)- then the design constraints of future stellarators might be relieved: a strict control of the magnetic shear (i.e., internal currents) would no longer be necessary and the available configuration space to optimize other physics aspects (for example, magnetic ripple, field symmetries to improve neoclassical transport, etc) would expand.

In the process of answering the questions posed above (goal beyond this article) a first step would be to summarize some well-established results from low shear devices. In the following subsections we try to survey the major effects of the low order rationals on confinement and transport. In section 4 we put the emphasis on the effect of magnetic shear through its impact on the low order rationals.

3.1 Degraded confinement due to low order resonances at low β

As is well known, in the absence of magnetic shear, low order resonances placed in the confining region produce large magnetic islands, which cause confinement degradation. The stellarators of the Wendelstein line have documented this result extensively [14, 23–25].

In Heliotron J, a clear transient degradation of confinement was observed around ι_a = 0.59 - 0.62 for ECH+NBI plasmas ($\langle\beta\rangle < 0.5\,\%$) with accompanying bursting coherent magnetic fluctuations with $m \sim 5/n = 3$. On the other hand, no obvious degradation of confinement was observed around ι_a = 0.49 - 0.50 despite the existence of the $m \sim 2/n = 1$ mode [26].

In TJ-II, stationary situations of degraded confinement are not easy to find. The reason for this basic difference with the W7-AS phenomenology is not yet understood but it might have to do with the fact that TJ-II is not operated with feedback control of the plasma current by the OH transformer. In conditions of high ECR heating power density ($\approx$ 15 W/cm^{-3}) and low plasma density ($\approx$ 0.5 - 0.7$\times 10^{19}$ m^{-3}) transient degraded confinement states —sometimes interspersed with phases of improved confinement— are observed in TJ-II in a variety of different experimental conditions, normally associated to the presence of low order rationals. The experimentally measured characteristics of the features associated to the observed transport events depend on the position of the resonance [27, 28]. Examples are: fast transient drops of the electron temperature associated to the 3/2 and 8/5 resonant surfaces close to the plasma centre [29]; or transient flattenings of the electron temperature profile (ELM-like events) associated to the presence of the 3/2 resonant surface in the density gradient region [30, 31].

A clear case of flattening of the pressure profile in TJ-II is shown in Fig. 3, where a Thomson Scattering profile measured in an ECH discharge with induced OH current to study magnetic shear effects is shown. The time evolution of the rotational transform can be estimated considering the measured net current as due only to the OH

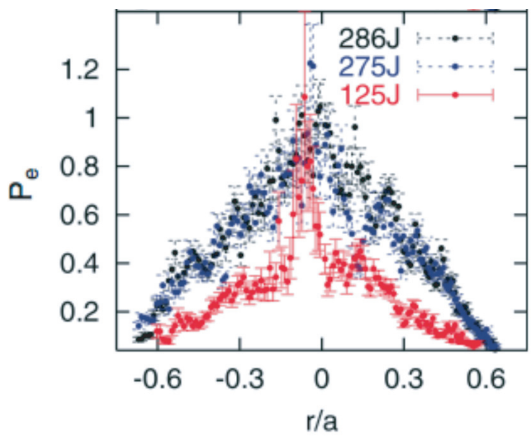

Fig. 3 Pressure profile (Thomson scattering) for three reproducible discharges with induced OH current. Black and blue profiles are measured at t = 1125 ms. A clear flattening is produced at t = 1170 ms (red) (see also Fig. 4).

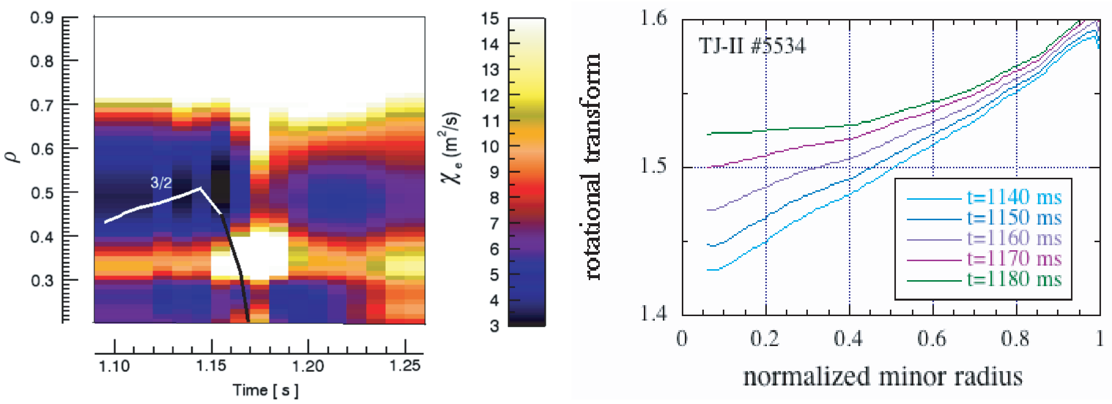

Fig. 4 Left: Time evolution of the effective $\chi_e \propto (\nabla T_e)^{-1}$ profile obtained from ECE data for a TJ-II ECRH discharge with small induced OH current. The evolving profile has its 3/2 value moving as shown by the black/white line. Right: Corresponding evolution of the rotational transform.

transformer and taking into account the evolving T_e profiles from the ECE diagnostic. As the plasma current density diffuses inwards due to the effect of (Spitzer) resistivity, it is found that the 3/2 ι-value disappears from the plasma at $t \approx 1170$ ms with null shear. An effective χ_e is obtained simultaneously from power balance calculations. The results shown in Fig. 4 are a clear indication that the short transient with large χ_e (or small ∇T_e) around 1170 ms seen in the experimental data are a consequence of the $\iota = 3/2$ resonance occupying a fraction of the plasma core, thus causing a transient flattening of the T_e profile [32]. It is worth emphasizing that the use of this effective χ_e allows us to study and quantify the effect of resonances on local transport without the need to identify its ultimate cause (ergodization, turbulence, loss of confining volume or any MHD-related phenomenon).

Note that the presence of the 3/2 resonance (white/black line in Fig. 4) does not really alter transport unless something in the rotational transform profile favours a singular effect of transient nature. Despite the approximated character of these calculations, the figure suggests that the transient of large diffusivity at $t \approx 1170$ ms, coincident with the narrowed profiles shown in Fig. 3, is a consequence of the ι-profile having been forced by the OH current to flatten and occupy a portion of the plasma with very small shear. It is worthwhile noting that, after the clearly degraded transport at $t \approx 1170$ ms due to the 3/2 resonance in no shear condition, the resonance disappears completely from the plasma due to the larger induced current. In spite of this, after the crash, the transport coefficient remains larger than before it. This behaviour is attributed to the fact that the shear continues decreasing in the external part of the plasma [33] as Fig. 4 (right panel) illustrates. We shall come back to this in Sec. 4.

In early W7-AS works, transient phenomena which might resemble some of the transient TJ-II events just outlined above were mentioned: transient maxima of energy confinement interspersed with phases of degraded confinement have been reported in the transient phase of plasma build up (very low or even negative shear), still without feedback control of the plasma current and with ι-values close to low order rationals [14].

3.2 Improved transport in the vicinity of low order resonances

W7-AS results show that narrow optimum confinement windows with smaller transport are located close to (but no at) the low order resonances. The explanation given for this result is based on an empirical model, which assumes that transport is always enhanced at resonant surfaces and that this enhancement is reduced by magnetic shear [22]. This model invokes the rarefaction of high order resonances in the immediate vicinity of low order ones, which is expected to decrease the turbulent transport.

There is abundant experimental evidence of the role of low order resonances as triggers for different improved transport events [28]. Transport barriers close to resonant surfaces have been found in tokamaks [34, 35]. Several stellarators like LHD and TJ-II have also found electron transport barriers close to rational surfaces located in the core region [36–40] or in the plasma edge [41, 42]. In TJ-II low collisionality plasmas, when the 3/2 resonance is in the core, an increase of the positive radial electric field is measured, synchronized with the electron transport barrier formation [38, 43]. The phenomenon is similar to the improved heat confinement found in the neoclassical electron root feature in several stellarators, the so-called CERC [44, 45]. Recent experiments in TJ-II, in low collisionality plasmas, have shown also for the first time an increase in the central ion temperature, simultaneous to the increase of electron temperature and triggered by the 4/2 resonant surface [46].

Heliotron J has reported experimental evidence of rotational transform windows for the high quality H-mode, which is defined by the condition ($\tau^{\exp}/(f\tau^{\mathrm{ISS04}}) > 1.5$) close to the low order rationals of the vacuum rotational transform at the last closed flux surface (LCFS), as shown in Fig. 5. In these windows, Langmuir probe measurements show reduced fluctuation-induced transport in the plasma edge region. Simultaneously, a negative radial electric field E_r (or E_r-shear) forms near the LCFS at the transition. The power and density thresholds of the H-mode are observed to depend on the rational surface, but the systematic dependences between them are not fully understood at present [20]. It might have to do with the influence of the topology (shape) of the magnetic surfaces on the poloidal viscous damping rate [21, 47].

3.3 Tracking the local lowering of χ_e due to low order rationals in TJ-II plasmas

In this section the results of local power balance analysis of a series of TJ-II discharges obtained in several magnetic configuration scans in TJ-II are presented [48]. The low order rationals included in this scans have poloidal mode number m in the range $2 < m \leq 6$. In TJ-II, one possible way of scanning the rotational transform profile through the confined plasma consists of varying in small steps (down to 0.1 kA) the current through the helical coil, which is the one with strongest effect over the ι value, and keeping the currents in the rest of coils essentially unchanged. This procedure, in a shot-to-shot basis, allows "sweeping" a certain low order rational through the confined plasma region in a very controlled way, in a close-to-vacuum shear condition, as shown in the left panel of Fig. 6. Note the narrow ι-span of this scan ($1.60 \leq \iota_{\rho=0.75} \leq 1.71$). The consequences of this scan of the rotational transform in χ_e as obtained from power balance calculations are shown in Fig. 6, in the form of a contour plot. The experimental data have been interpolated linearly along a rotated mesh aligned with the path of the $\iota = 8/5$ in the range $0.6 < \rho < 0.8$ (see [48] for details). The white solid and dashed lines correspond to the path followed by the lowest order rationals of the vacuum-configuration present in the scan (from left to right, $\iota = 8/5$, 13/8, 18/11 and 5/3). The figure shows a pattern of "ridges" and "grooves" whose direction follows roughly the path of rationals along the minor radius as I_{hc} increases (i.e., as the rationals move inwards). Therefore, the power balance analysis suggests that low order rationals retain heat fluxes at their radial location. This is very likely for $\rho > 0.6$, where ι should be practically the vacuum one due to the small net plasma currents typically found in these experiments. At this respect, preliminary estimations of the bootstrap current [49] indicate that there should be a change of sign near half radius, according to which the net current would approach zero as one moves inwards in radius up to $\rho \approx 0.6$, making the vacuum ι to be even closer to the one with plasma. All these aspects require further study and a careful estimation of internal currents. However, taking as a hypothesis that the grooves are coincident with the low order rationals, the proximity of the grooves and the location of vacuum val-

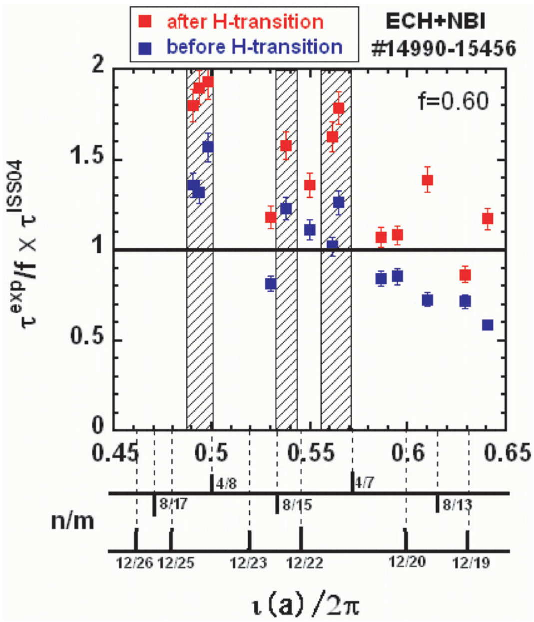

Fig. 5 Quality of the confinement improvement in the L to H transitions found in Heliotron-J depending on the edge rotational transform. The shadded areas mark optimum transitions.

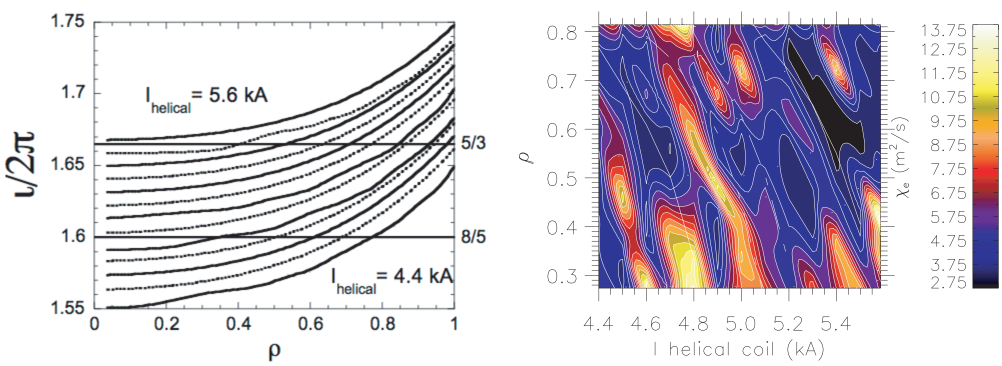

Fig. 6 Left: ι profiles for the set of 13 magnetic configurations of a iota-scan in TJ-II. Right: Contour plot of the effective ι obtained from TS data for the same set of magnetic configurations labelled by their helical coil current. Each profile is an average over a few discharges with similar line density.

ues of the low order rationals in Fig. 6 would be indicating that the bootstrap currents are indeed small in TJ-II ECH discharges. Finally, Fig. 6 corresponds to a very small portion in (ι, $\hat{s}$) as marked in Fig. 1. The reason is that, as seen in the left panel of Fig. 6, there is no shear scan in this experiment and the range of ι values is purposely small in order to follow the displacement of resonances in minor radius. The important fact, however, is that the corresponding low shear area marked in Fig. 1 allows for normal magnetic confinement despite the presence of low order rational values of ι.

4. The Role of Magnetic Shear

There is a robust experimental evidence showing that the confinement degradation produced by the presence of low order rationals in the confined plasma is restored if enough magnetic shear is generated, no matter the origin of the current (pressure driven, inductive, EC driven) [24]. An example from W7-AS is shown in Fig. 7, which shows the effect of ι_a and plasma current (using the OH transformer) on the plasma energy content, for discharges with identical plasma radius and densities. The strong dependence on rotational transform of the energy content, at zero current, decreases as the current is raised and disappears at the highest current value.

Local power balance analysis also provides clear evidence of restoration of degraded confinement via magnetic shear in W7-AS, as illustrated in Fig. 8. It shows degraded confinement in the no shear situation (0 kA). Increasing the shear with inductively driven current, reduces strongly the electron heat diffusivity in the gradient region. The discharges with I_p = 10 kA and 25 kA have ι = 1/2 in the plasma region without any significant local degradation of confinement. It is clear that confinement improves with shear independently of the sign.

It was mentioned before (see Fig. 4) that the effective χ_e, after a low order resonance has disappeared, can keep on increasing in TJ-II ECH plasmas with ohmic currents. This is an indication that something not related with the low order resonance itself is playing a part in the evolution of the discharge. These first experiments with OH in TJ-II [32] put the magnetic shear as one possible intrinsic cause of the effect on confinement, separated from the presence or not of low order resonances. Later dedicated experiments showed that small shear values, with absolute value of the order 0.1, are enough not only to allow includ-

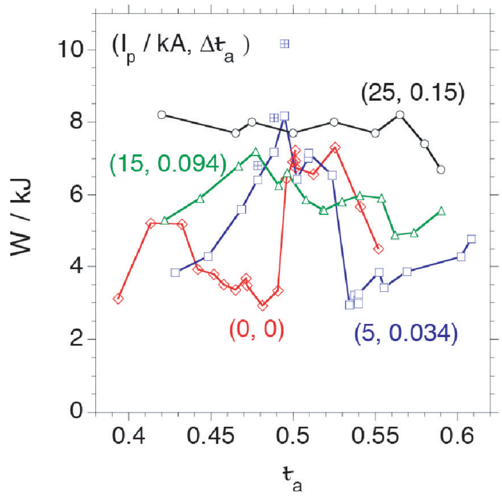

Fig. 7 Plasma energy content vs. ι for four values of induced OH current.

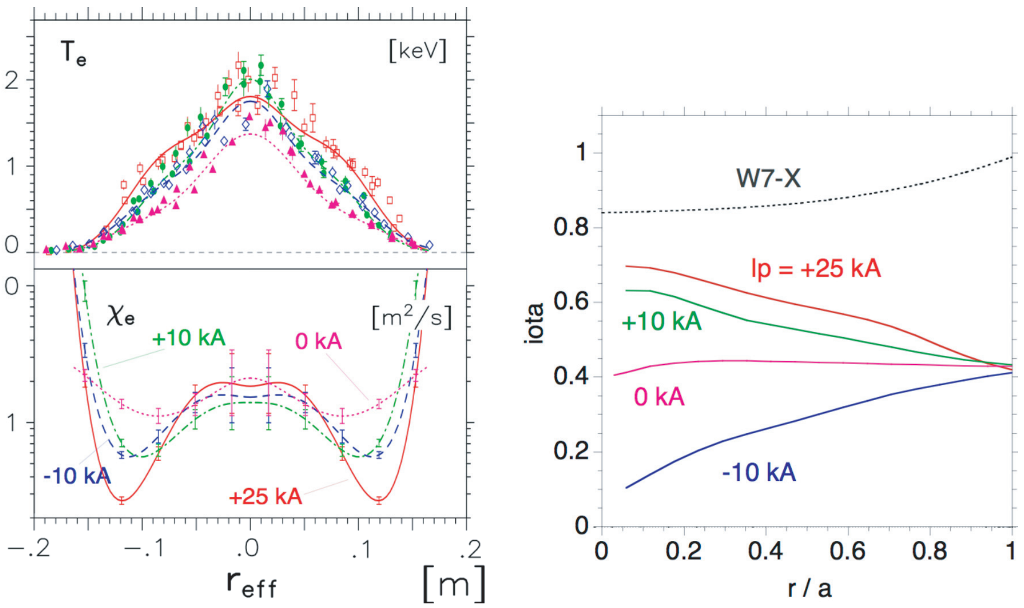

Fig. 8 Left: T_e (upper box) and χ_e (lower box) profiles for discharges with ι_a = 0.42 and different values of plasma current in W7-AS. Right: corresponding ι-profiles.

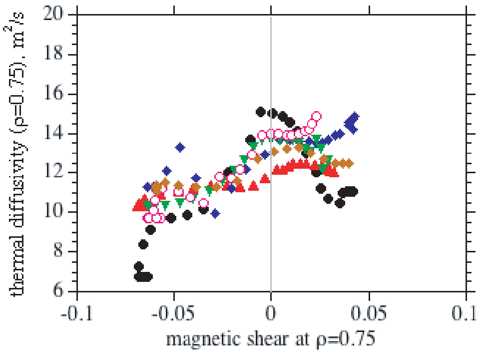

Fig. 9 Electron thermal diffusivity at $\rho = 0.75$ vs. magnetic shear in the same radial position for several discharges with induced OH current in TJ-II.

ing the lowest order rationals inside the plasma but even to force the transport to decrease in the gradient region obeying the shear strength [33]. Figure 9 shows the effective thermal diffusivity obtained in $\rho = 0.75$ for a number of different ECRH discharges with similar density, in plasmas operated under ohmic induction. Positive induction drives ι towards positive values although high $\hat{s} > 0$ values cannot be reached because the largest plasma current ($\approx$ 10 kA) does not allow for further variation of the rotational transform profile. According to these results, the largest χ_e is found around zero shear and it clearly decreases for negative shear. Positive shear seems also to reduce transport although the result is less clear due to the smaller explored range. These TJ-II results are in line with the W7-AS conclusion.

5. Summary

- Keeping the configuration free of low order resonances in real experimental conditions is a difficult task for devices with low vacuum magnetic shear. The optimized design of Wendelstein 7-X will allow it to fully explore and characterize this scenario at high β. The fine-tuning capability of the available modern ECRH systems provides an additional tool, if needed, to compensate undesired internal currents by means of localised heating.
- Certain amount of shear allows the presence of even the lowest order rationals (1/2 in the W7-AS case) within the confinement region without degradation. Low shear values, $|\hat{s}| \approx 0.1$, are enough in TJ-II —which is the stellarator with highest ι— to observe the beneficial effect of the shear. Further comparisons between devices with different ι are needed in order to study whether there is a threshold value for the shear that depends on the ι value.
- Narrow optimum confinement windows are found in W7-AS and Heliotron-J close to low order rational values. Provided a small amount of magnetic shear is present, the low order resonances are found to trigger a variety of improved transport events in TJ-II. Fine configuration scans in this machine have shown that low order rationals retain heat fluxes at their radial location.
- Both W7-AS and TJ-II results show that the beneficial effect of shear on confinement does not depend on the sign.
- Many of the results presented in this paper are based on local heat balance analysis. A word of warning concerning the ISHCDB must be considered seriously in this respect: W7-AS has shown that also the particle confinement can depend on ι and shear [50]. This fact could give rise to misleading conclusions if only the power balance is considered because quite different T_e profiles, indicating a degraded global τ_E, could have a negligible impact on the local χ_e. So, complete analysis of temperature and density profiles would be needed.

This work contributes to the International Stellarator/Heliotron Confinement DataBase (ISHCDB) under auspices of the IEA Implementing Agreement for Cooperation in the Development of the Stellarator Concept [12].

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