International Stellarator/Heliotron Database Activities on High-Beta Confinement and Operational Boundaries

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Abstract. The ISS04 scaling of the energy confinement in stellarators/helical systems has been derived from selected data of the International Stellarator/Heliotron Confinement Database (ISHCDB), taking only few high-β data into account. Therefore, the basis for extrapolations to the reactor regime is insufficient. In the last years, regimes with reactor relevant beta became accessible in the Large Helical Device (LHD) and the W7-AS Stellarator. The high-β confinement regime is close to operational boundaries determined by degradation of the equilibrium surfaces, by stability limits of pressure driven MHD modes and by available heating power. This may lead to limits of the confinement and to modifications of scaling laws due to changes of the underlying physics. Therefore, an effort is made to establish and to extend the high-β data subset in the ISHCDB. The data are compared with existing scaling laws and predicted operational limits. The magnetic configuration has a significant impact on the confinement. In particular, a deterioration of the confinement with increasing beta is found in LHD which can partially be attributed to changes of the configuration. In order to identify the most important physical effects additional parameters are required to characterize the local transport and the predicted and experimental MHD properties.

1. Introduction

The ultimate goal of the international stellarator program is to provide a basis for a economically attractive fusion energy source. The prospects of the manifold of different configurations and approaches have to be assessed by inter-machine comparisons of the achieved global plasma parameters and local transport properties. Likewise, the collection of reference data from existing machines will allow to evaluate the benefit of configuration optimization as anticipated in the new W7-X [1] and NCSX [2] devices being presently under construction[1]. Scalings of the global confinement have been established based on the analysis of different low-β ECRH (electron cyclotron resonance heating) and NBI (neutral beam injection) scenarios investigated in several stellarators and helical devices [3]. An extended ISHCDB database (including a first high-β dataset from W7-AS) resulted in the proposal of a new unified scaling of the confinement time in stellarators based on empirical renormalization factors depending on the configuration or device [4]. In order to get a more detailed understanding of the energy transport in stellarators and helical devices the international database effort is presently extended by the so-called International Stellarator/Heliotron Profile Database (ISHPDB) [5]. This activity attempts the documentation and analysis of 1-d and 2-d data for various topics including local energy and particle transport. With regard to high-β physics, first studies of the effect of the magnetic configuration on the local transport in LHD high-β discharges have been made [6]. In addition, the definition of an appropriate set

[1] The NCSX project was closed in 2008

of configuration and plasma parameters is required to characterize the dependence and impact of ideal and resistive MHD modes on the magnetic configuration [7].

A compilation of high-β results in LHD and W7-AS including comparisons among each other as well as to tokamak results can be found in refs. [8], [9], [10], [11]. Until 2006/2007 further significant progress has been achieved in LHD reaching volume averaged values of $\langle\beta\rangle \approx 5\%$ [12]. These new data are particularly important to include in the ISHCDB/ISHPDB, since they bridge the gap to the reactor relevant β-values. Key issues concern the β-dependence of the confinement and the physical mechanisms determining the achievable stationary level of $\langle\beta\rangle$.

The use of the database for inter-machine comparisons depends crucially on a clear definition of a set of key parameters and on standardized analysis procedures. However, in the high-β regime the configuration changes with β, and hence some parameters are not easily accessible, and their definition has to be reconsidered. Most importantly, the identification of the plasma boundary and hence the determination of the effective plasma radius requires a more sophisticated analysis, since the plasma edge region of high-β plasmas is usually characterized by stochastic field layers where a significant pressure gradient is still maintained [13], [14], [15]. For practical reasons, the measured pressure profiles are mostly fitted by equilibria based on the assumption of nested flux surfaces as calculated with the VMEC code [16]. In LHD, the flux contour which contains 99 % of the measured kinetic plasma energy has turned out to be the most appropriate measure of the plasma edge location.

In W7-AS high-β discharges are effectively limited by the divertor structures, and therefore the plasma boundary is identified by the intersection of flux surfaces with the divertor. This is achieved by using the STELLOPT code [17] which is based on VMEC and iterates for equilibria consistent with the measured diamagnetic energy and kinetic data [18]. The pressure induced shift of the plasma axis can be compensated by an appropriate vertical field so that plasmas with the maximal possible plasma volume could usually be established.

In this paper, the main focus is to characterize and compare different sets of high-β data from LHD and W7-AS and to discuss their implementation in the ISHCDB. Some preliminary results on the scaling of the global confinement will be presented. In particular, the W7-AS high-β dataset is used to identify differences in the confinement compared to low-β plasmas by a probabilistic model comparison approach [19], [20]. Finally, some remarks about possible extensions towards MHD related data will be made.

2. W7-AS High Beta Data

A first database consisting of about 200 entries was compiled in 2003 [8] based on cases for which dedicated VMEC or STELLOPT calculations were made for different reasons. Standard parabolic pressure profiles were used in the VMEC calculations and (small) net-currents were modeled with a standard current profile. In single cases it could be shown that the experimental pressure profiles were close to parabolic apart near the plasma edge. The equilibria were calculated in such a way as to reproduce the measured diamagnetic energy and the plasma boundary just in contact with the plasma facing structures (divertor troughs). Most of the configuration parameters (effective plasma radius *a*, axis position, values of the rotational transform, volume averaged magnetic field, etc. as well as plasma data such as $\langle\beta\rangle$ were taken from the VMEC calculation.

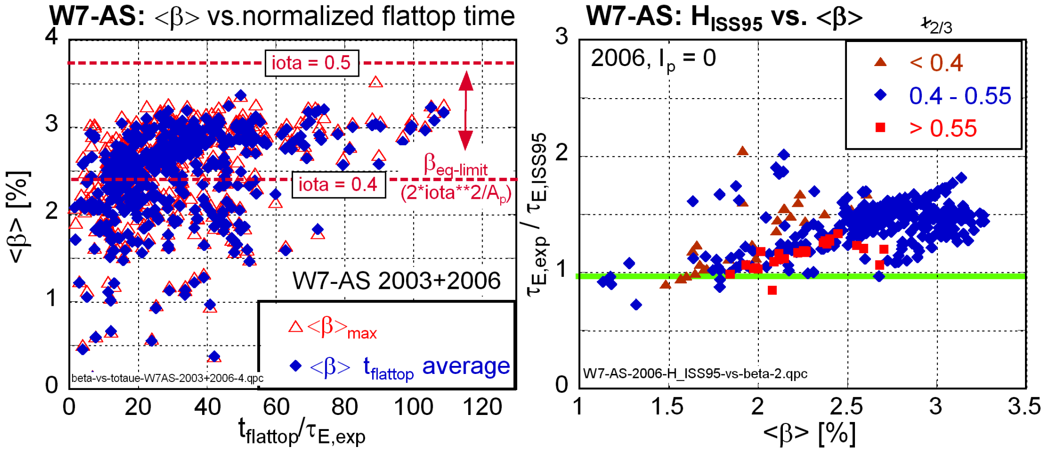

***FIG. 1.** Left: $\langle\beta\rangle$ from the combined W7-AS survey datasets versus the time (normalized to $\tau_{E,exp.}$) in which $\delta\langle\beta\rangle/\langle\beta\rangle \le 10\%$ (as a measure of the stationarity of the discharges). The horizontal dashed lines mark simplified estimates of an equilibrium limit for two configurations of different rotational transform in the W7-AS device, taking the reduction of the Shafranov shift by a factor of two (resulting from stellarator optimization in W7-AS) into account. Right: Energy confinement times normalized to ISS95 (combined W7-AS datasets). The data refer to different configurations. The ISS04 renormalization factor according to [4] for these data is $f_{ren} = 0.86 \pm 0.18$.*

A second compilation was made in 2006 using a systematic W7-AS database search that was constrained to find all high-β cases without significant toroidal plasma current. In a second step, only discharges were selected, which showed a quasi-stationary behaviour (for $\Delta t \gg \tau_E$). Using one or more time points per discharge during quasi-stationary periods almost 400 entries in this database were generated. The data cover a variety of different configurations with the majority of cases close to the optimum confinement at $\iota \approx 1/2$ (rotational transform, iota). The achieved β-values in W7-AS taken from a combination of the 2 datasets are shown in Fig. 1 (left part) plotted versus a time (normalized to the confinement time) characterizing the duration of the quasi-stationary period around the β-maximum. The dashed horizontal lines indicate equilibrium limits based on a simple model for a critical Shafranov shift ($\Delta = 0.5a$) for two particular configurations differing in the rotational transform. The Shafranov shift is considered to provide a good index for the deformation of magnetic flux surfaces. Whereas in low-iota configurations the maximum achieved beta is clearly limited by equilibrium effects, the maximum beta at higher iota is mainly determined by the available heating power. The corresponding energy confinement times normalized to the values predicted by the ISS95 scaling [3] are given in the right part of Fig. 1 as a function of $\langle\beta\rangle$. The experimental and numerical assessment of the absorbed NBI heating power is subject of relatively large errors due to the increased fraction of injected NBI ions suffering direct orbit losses at low magnetic field (the high-β data were obtained with toroidal magnetic fields in the range $B_t = 0.75$ T...1.25 T). Although a detailed equilibrium analysis with the PIES code [15] revealed a deterioration of the local transport in the outer plasma region with increasing beta due to the expansion of the stochastic layer, no such evidence is found in these global confinement data. Modelling of high-β equilibria with PIES for a few selected W7-AS cases required a modification of the original code to retain the experimentally observed pressure profiles. Fig. 2 shows an example of a Poincaré plot corresponding to a PIES equilibrium of a $\langle\beta\rangle = 1.9\%$ case. It has to be noted that the plasma cross section in W7-AS varies between triangular and horizontally elongated shapes within each of the five toroidal field periods. The outermost contour in the Poincaré plot indicates the boundary as found by a VMEC/STELLOPT calculation which served as a start configuration for PIES. Similarly as found in LHD (see next section), pressure and pressure gradients exist in the stochastic region (with embedded remnants of magnetic island chains) up to the VMEC boundary which is in contact with limiting structures. The degree of stochasticity can be mitigated to some extent by using a set of so-called control coils which are normally used for island divertor optimization. Actually, this has proven to be a key element for achieving $\langle\beta\rangle > 3\%$ in W7-AS.

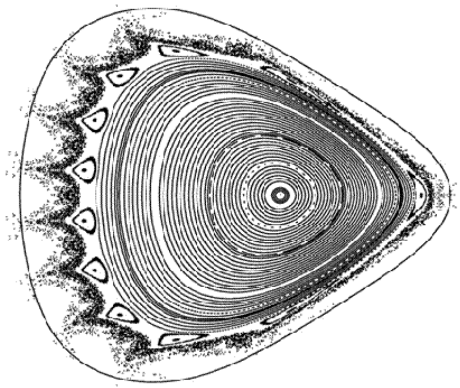

FIG. 2. *Beta induced formation of a stochastic field layer in a W7-AS finite-β equilibrium ($\langle\beta\rangle = 1.9\%$) as reconstructed with the PIES code. The vacuum configuration has a flat rotational transform around $ι_{vac} \approx 0.45$. Plasma pressure is sustained up to the plasma boundary as determined by the STELLOPT code (outermost contour).*

3. LHD High Beta Data

The first comprehensive survey of high-β data from the 7th and 8th experimental campaign using a similar constrained database search [10] was revised and extended up to the 10th campaign (2007) during the present study. Three datasets with altogether about 806 selected entries referring to configurations with a vacuum axis position of $R_{ax} = 3.6$ m and helical coil (HC) pitch parameters of γ= 1.25, 1.22 and 1.20 were compiled at the maximum of the diamagnetic energy within each discharge. Here, the pitch parameter is defined by $\gamma = M/L/A_c$, where L=2, M=10, A_c=3.6-4.4 (number, periods and aspect ratio of HCs). The aspect ratio of the HC was varied by changing the current ratio in the three HC layers resulting in plasma aspect ratios of A_p = 5.7, 6.1 and 6.5. These configuration parameters refer to the vacuum configurations. Since the rotational transform in LHD scales as $A_p \sim ι$, the Shafranov shift is $\Delta/a \sim 1/A_p$, and hence is progressively reduced in configurations with decreasing γ parameter. This has proven to be a key to maximize the achievable beta. The $\langle\beta\rangle$ values achieved in these 3 configurations are shown in Fig. 3 in a similar form as the W7-AS data in the left part of Fig. 1. Parameters of the vacuum configurations (plasma volume, volume averaged magnetic field) and diamagnetic measurements of the plasma energy were used in the evaluation taken from the

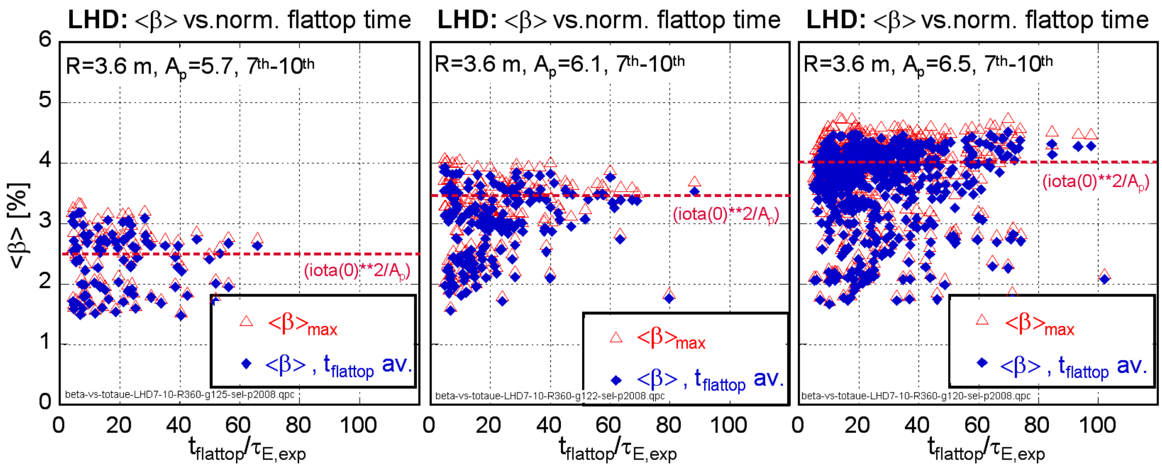

FIG. 3. *$\langle\beta\rangle$ values from the three new LHD survey datasets with $R_{ax} = 3.6$ m, $\gamma = 1.25, 1.22, 1.20$ (corresponding to aspect ratios of $A_p = 5.7, 6.1, 6.5$ of the vacuum configurations) versus the time (normalized to $\tau_{E,exp.}$) in which $\delta\langle\beta\rangle/\langle\beta\rangle \leq 10\%$. The horizontal dashed lines represent crude estimates of equilibrium limits in a low-shear stellarator which underestimate significantly the predicted equilibrium limits of the high-shear LHD configurations.*

LHD database. The dependence of the maximum achievable β values on the aspect ratio or the rotational transform shows a correlation with $\langle\beta\rangle_{crit} \approx \iota^2/A_p$ (horizontal dashed lines) which defines an equilibrium limit for a classical low-shear stellarator and which is taken as a reference. Here, the central rotational transform is used. Therefore, the actual limits for LHD are significantly larger because of the large positive shear in the ι-profile. Actually, the observed Shafranov shift stays clearly below the critical value (half of the minor radius), even at the maximum beta of 5%, where $\Delta/a \approx 0.33$. It should be noted that for W7-AS $\langle\beta\rangle_{crit} \approx 2\iota^2/A_p$ was taken due to the reduction of the Shafranov shift by configuration optimization [8]). Detailed equilibrium investigations with the HINT code [14] show field line stochastization effects in the plasma boundary region depending on the magnetic configuration and on β. Typically, the measured pressure profiles extend across the stochastic edge region up to or even beyond the boundary of the vacuum configuration. This is attributed to the relatively large connection lengths of the stochastic field lines compared with the electron mean free path lengths in the high collisional edge region. In Fig. 4, a HINT equilibrium for a $\langle\beta\rangle \sim 3\%$ case is given, corresponding to the maximum beta achieved experimentally in the $\gamma = 1.254$ ($A_p = 5.7$) configuration. The width of the stochastic layer seems to be too small to account for the limitation of β due to the destruction of equilibrium surfaces. However, the impact of the quality of finite-β flux surfaces on the transport has to be investigated further in more detail. Modelling studies of field line diffusion effects with the HINT code are underway to assess these effects quantitatively. Although the HINT results do not provide yet a clear direct evidence of an equilibrium limit at maximum β, it appears that the confinement deteriorates when the Shafranov shift reaches a critical value. The Shafranov shift is associated with flux compression, which leads to a steepening of surface averaged profile gradients and hence increased transport fluxes [21]. Therefore, this effect of the flux surface geometry could contribute to the limitation of $\langle\beta\rangle$ without invoking flux surface destruction.

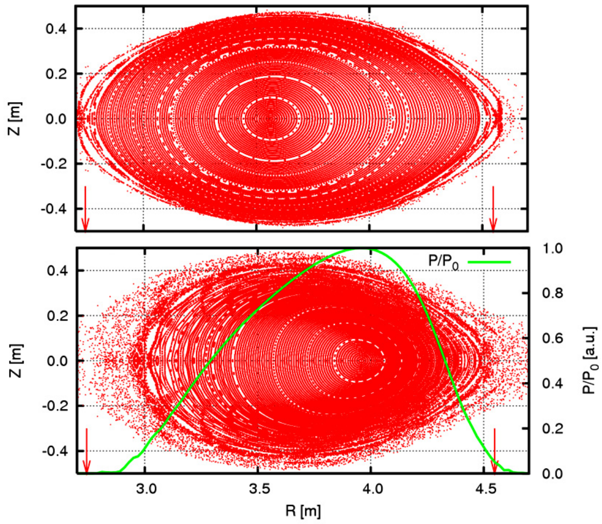

FIG. 4. *Modification of the magnetic field structure by finite-β effects in LHD modelled by the HINT code. For comparison, the vacuum configuration is shown on the top. The lower part contains an equilibrium corresponding to the maximum beta achieved in the $R_{ax} = 3.6$ m, $\gamma = 1.25$ configuration, where $\langle\beta\rangle \sim 3\%$. Plasma pressure is sustained across the stochastic field region at the plasma boundary.*

Besides of its direct connection with an equilibrium beta limit, a large Shafranov shift (see fig. 4) also leads to unfavourable NBI power deposition and subsequent large direct fast ion losses at low magnetic fields as calculated by the FIT code [22]. This results in different operational limits at low magnetic fields and differences in the achievable beta depending on the configuration, and may therefore provide an alternate explanation for the dependence on the γ-parameter in fig. 3. On the other hand, any configuration dependent MHD stability effects can be excluded, since the observed magnetic fluctuation levels, mostly due (m,n) = (3,2) modes located in the edge region, are largest in the optimized configurations with higher β-limits.

In the three survey datasets the vacuum boundary was used for the evaluation of the confinement scaling laws. The vacuum boundary is close to the contour encompassing 99% of the total pressure at high beta. In contrast, the ideal finite-β equilibrium calculations give lower values for the plasma radius. Here, some discrepancy between HINT and VMEC as regards the magnitude of the Shafranov shift has to be stated which is not yet fully understood. Although the HINT results are in better agreement with the experimental data, VMEC data are still widely used because much more pre-calculated equilibria are available in the LHD equilibrium database. The values of the rotational transform and of the plasma position required for the global scaling law predictions have been derived using interpolations between pre-calculated VMEC equilibria which were selected to reproduce the available experimental data related to the flux surface geometry.

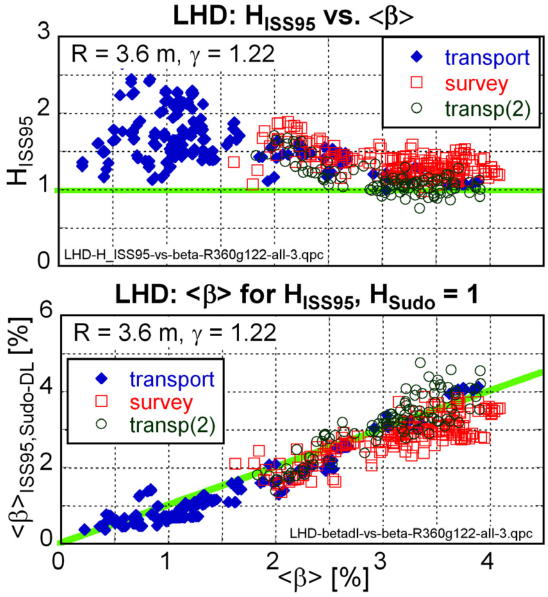

FIG. 5. Top: Energy confinement times normalized to ISS95 (H_{ISS95}) for the LHD γ=1.22 configuration (3 different datasets, which yield an renormalization factor of $f_{ren} = 0.87 \pm 0.21$). Bottom: Predicted confinement limit of $\langle\beta\rangle$ compared with experimental values, assuming H_{ISS95}=1 and densities at the Sudo-limit.

Typically, the averaged densities of the LHD high-β datasets reach the Sudo-limit [23], particularly in the upper range of β. The density limit in stellarators is not an absolute limit but depends on the available heating power. In Fig. 5 we discuss whether the experimentally observed β-limit could likewise be determined by the properties of the global confinement scaling. The upper part shows the experimental global confinement times normalized to the ISS95 scaling as a function of $\langle\beta\rangle$ in the case of the inward shifted configuration with $R_{ax} = 3.6\,\text{m},\ \gamma = 1.22$. Here, the survey data are compared with two other datasets, which have been compiled for detailed confinement and MHD studies during stationary time intervals and using a comprehensive analysis of plasma and configuration parameters. The progressive degradation of the confinement towards high beta has been described earlier [24] and attributed mainly to the beta-induced changes of the flux geometry parameters (outward shift of the configuration) [6]. Only close to the plasma periphery additional transport effects are indicated. The maximal values of $\langle\beta\rangle$ which can be expected for a given heating power were estimated by using the ISS95 confinement scaling and taking the Sudo limit as the maximum for the achievable density. The experimental β-values are close around this reference (see lower part of fig. 5), and hence the analysis suggests that the limits of $\langle\beta\rangle$ are also roughly consistent with the transport underlying the ISS95 confinement scaling. The dependence of the scaling values on the γ parameter of the different configurations is mainly due to differences in the flux surface geometry parameters.

4. Discussion and Conclusions

The inclusion of high beta data from W7-AS and LHD in the ISHCDB data base provides an important test for the validity of existing scaling laws in the high-β regime and can lead to more reliable extrapolations to the reactor regime. In order to achieve this goal, results of local transport analyses have to be supplemented in the frame of the ISHPDB activity. This is currently in progress based on selected configurations in LHD [6][25] and W7-AS. Also, detailed information about the mechanisms that limit the achievable β and about their dependence on the magnetic configuration can be expected in conjunction with advanced equilibrium modeling (eg. by HINT or PIES) allowing to assess effects of field line diffusion. The first rough global confinement analysis presented in the previous chapters provides only limited and ambiguous information.

In addition, the quality of extrapolations from the parameter space covered by the present database will be enhanced if the observed dependencies of the data (confinement times or local diffusivities) on the control parameters are consistent with basic physics models. For this purpose Bayesian probability theory for model comparison was used and applied to subsets of W7-AS low-β and high-β global confinement data [19][20] to determine the model out of six so-called Connor-Taylor models [26] which provides the best fit to the experimental data. The model comparison approach uses a generalized power law ansatz for the plasma energy of the form

$$W^{theo} = na^4B^2\sum_k c_k \left(\frac{P}{na^4B^3}\right)^{\xi_{1k}} \left(\frac{a^3B^4}{n}\right)^{\xi_{2k}} \left(\frac{1}{na^2}\right)^{\xi_{3k}} \qquad (1)$$

which also allows a refined analysis of the global confinement including the description of saturation effects in the control parameters such as the averaged density n or the absorbed heating power P. The remaining control parameters are the magnetic field strength B and the effective plasma radius a.

According to the invariance principle of basic plasma model equations the exponents ξ in the generalized scaling relation (1) are subject to constraints depending on the used model [26]. Models that ignore any finite-β effects were found to fit the low-β data best, whereas collisional finite-β models gave the best agreement with the high-β data. Therefore, it is concluded that the global confinement depends on beta in this range. The Bayesian approach provides a confidence range where predictions and extrapolations can be trusted given the experimental errors. An example for the prediction of a single parameter dependence (here: density dependence) and comparison with a dedicated experimental parameter scan is shown in Fig. 6. The multi-parameter dependence according to (1) was derived from all data of the W7-AS high-β subset (open symbols) which are given here in terms of plasma energy as a function of plasma density. The solid line represents the resulting dependency on the density alone (all other control parameters kept constant) together with its confidence range

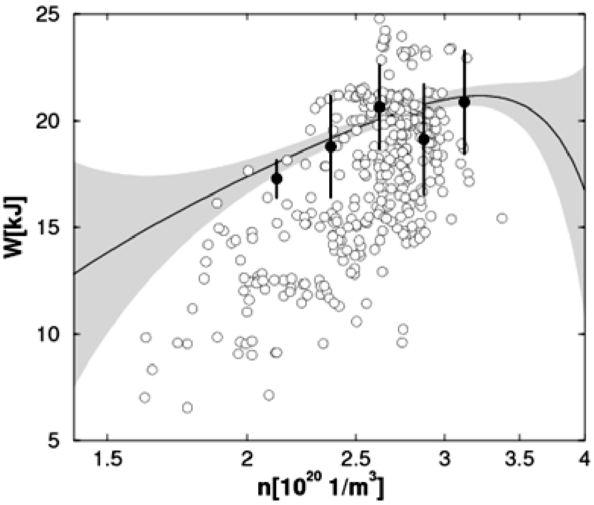

FIG. 6. *Scaling of the global confinement derived for a high-β data subset of W7-AS (open symbols) using constraints imposed by comparison with a collisional high-β Connor-Taylor model. The dedicated experimental density-scan (solid symbols) agrees well with the predicted curve (solid line), which was obtained from all data points. The shaded area marks a confidence range according to the Bayesian probability approach used in the analysis.*

(shadowed). The predicted curve agrees very well with the data of a dedicated density scan (solid symbols) which were not included in the original dataset.

Since the W7-AS high-β data are in a different collisionality region well separated from the LHD data, a similar model comparison analysis for LHD is required to confirm the results from W7-AS. This will be very important in order to assess the role of the collisionality as well. In LHD, a clear dependence of the confinement time (normalized to ISS95) on this parameter was found in the high collisionality regime [27]. Moreover, this survey indicates that LHD data even allow for a detailed assessment of the transition from low- to high-β regimes.

The high-β regimes in W7-AS and LHD are characterized by a parameter space which is close to operational limits depending on the configuration and on plasma parameters. In order to clarify the role of the configuration dependent beta limits imposed by confinement, equilibrium and stability effects, MHD related data including configuration parameters, data characterizing the MHD mode activity and its relevance for the global and local transport, data on local pressure profiles and results of numerical equilibrium and stability calculations are foreseen to include in the ISHPD in the next steps, in addition to data required for local transport studies.

This work contributes to the International Stellarator Profile Data Base (ISHPDB) under auspices of the IEA Implementing Agreement for Cooperation in the Development of the Stellarator Concept. The first author would like to thank for his invitation by NIFS as Foreign Guest Scientist.

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