Extensions of the International Stellarator Database by High-β Data from W7-AS and LHD

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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.

Keywords: Stellarator, Helical System, Confinement, Transport, High Beta, Confinement Database, Beta Limit, Magnetic Configuration

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 has 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. 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 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 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 particulary important to include in the ISHCDB/ISHPDB, since they bridge the

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gap to the reactor relevant β-vales. Key issues concern the β-dependence of the confinement and the physical mechanisms determining the stationary level of β.

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 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 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 approprate vertical field so that plasmas with the maximal possible plasma volume were usually 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 modelled 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

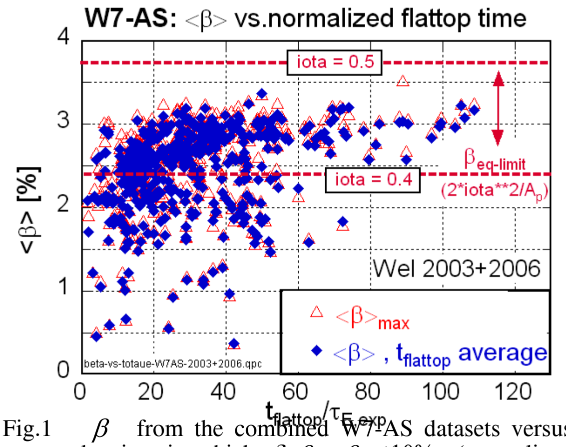

Fig.1 $\langle\beta\rangle$ from the combined W7-AS datasets versus the time in which $\delta\langle\beta\rangle/\langle\beta\rangle \le 10\%$, (normalized to $\tau_{E,\text{exp.}}$).

plasma boundary just in contact with the divertor trough. Most of the configuration parameters (effective plasma radius, 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.

A second compilation was made in 2006 using a systematic W7-AS database search that was constrained to find all high-beta 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 dataset 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). The achieved β-values in W7-AS taken from a combination of the 2 datasets are shown in fig. 1 plotted versus the time of the quasi-stationary period (normalized to the confinement time). The dashed horizontal lines indicate an equilibrium limit based on a simple model for a critical Shafranov shift for 2 particular configurations. Whereas in low-iota configurations the maximum achieved beta is clearly limited by equilibrium effects, the maximum

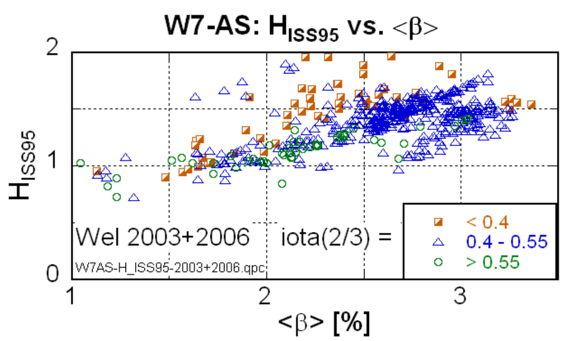

Fig.2 Energy confinement times normalized to ISS95 (combined W7-AS datasets). The data refer to different configurations. The renormalization factor according to [4] for these data is $f_{ren} = 0.86 \pm 0.18$.

beta at higher iota is mainly determined by the available heating power. The corresponding energy confinement times normalized to the ISS95 [3] scaling values are given in fig. 2 as a function of $\langle\beta\rangle$. Although a detailed equlibrium analysis [15] revealed a deteroration 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.

3. LHD High Beta Data

The first comprehensive survey of high-β data from the 7th and 8th experimental campaign [10] using a similar constrained database search was revised and extended up to the 10th campaign (2007) during the present study. Three datasets corresponding to 3 different configurations (3 helical coil current ratio parameters $\gamma = 1.25$, 1.22 and 1.20 corresponding to aspect ratios of $A_p = 5.7$, 6.1 and 6.5 at axis position $R_{ax} = 3.6\ \mathrm{m}$) with altogether about 1500 entries are compiled at the maximum of the diamagnetic energy within each discharge. All parameters refer to the vacuum configurations. Since the rotational transform in LHD scales as $A_p \sim \iota\!\!\!-$, the Shafranov shift is $\Delta/a \sim 1/A_p$, and hence is reduced in the $\gamma = 1.20$ configuration. This is a key to maximize the achievable beta. The $\langle\beta\rangle$ values achieved in the optimum configuration which are evaluated using parameters of the vacuum configurations are taken from the LHD database and are shown in fig. 3 in a similar form as the W7-AS data. The simple estimate of the equilibrium limit shows that the maximum beta values may already be affected by equilibrium limit effects (Note that for W7-AS the value has been doubled due to the configuration optimization [8]). Detailed investigations with the HINT code [14] show very extended regions of field line stochastization.

For the evaluation of the confinement scaling laws, the vacuum boundary was used, which is close to the 99% pressure contour at high beta. In contrast, VMEC gives much lower values for the plasma radius which is not consistent with the experimental data. However, the values for iota and the plasma position are derived from the available VMEC calculations.

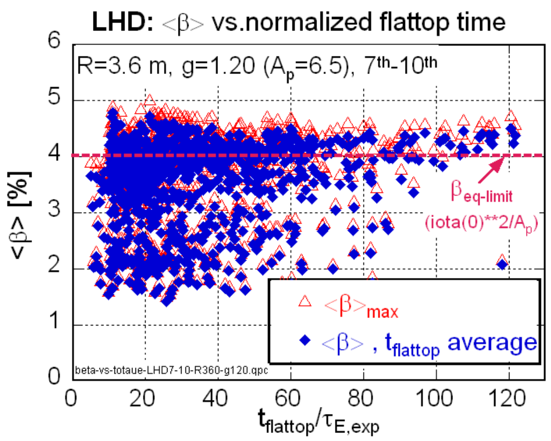

Fig.3 $\langle\beta\rangle$ from the new LHD survey dataset with $R_{ax} = 3.6\ \mathrm{m}$, $\gamma = 1.20$ versus the time in which $\delta\langle\beta\rangle/\langle\beta\rangle \le 10\%$, (normalized to $\tau_{E,\mathrm{exp.}}$).

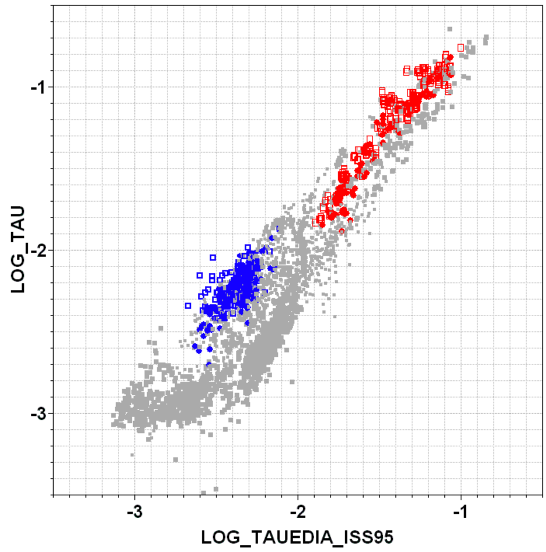

Fig.4 Logarithmic plot of $\tau_{E,\mathrm{exp.}}$ against the ISS95 scaling values. The data highlighted in blue represent the two W7-AS high-β survey datasets. In red, the two high-β datasets of LHD used for transport studies are shown (ISHCDB preliminary).

Two more detailed datasets for studies of the local transport behaviour and its dependence on the magnetic configuration ($\gamma = 1.25$ and 1.22 with $R_{ax} = 3.6\ \mathrm{m}$) have been compiled (about 450 entries) by the LHD team [6][21]. These data have been added in a preliminary way to the existing ISHCDB dataset. In Fig. 4, $\tau_{E,\mathrm{exp.}}$ is plotted in comparison with the ISS95 scaling values. The two datasets are highlighted in red together with the two survey datasets of W7-AS (blue) on the background data (grey) from all the existing low-beta ISHCDB data. A closer inspection of the LHD data (fig. 5) reveals a progressive degradation of the confinement towards high beta, which has been found already earlier.

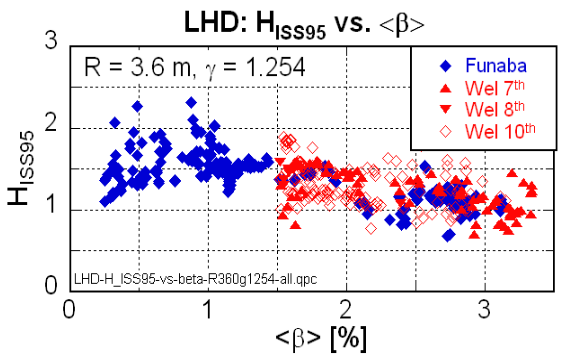

Fig.5 Energy confinement times normalized to ISS95 ($R_{ax} = 3.6\ \mathrm{m}$, $\gamma = 1.25$, comparison of different LHD datasets). A deterioration of the confinement is indicated towards high-β.

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][22].

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 a Bayesian model comparison method was applied to W7-AS low-β and high-β global confinement data [19][20]. The significance of the results depends crucially on the quality of the data and the knowledge of their errors. According to the invariance principle of basic plasma model equations the scaling parameters are subject to constraints depending on the model used [23]. Models that ignore any finite-β effects were found to fit the low-β data best, whereas 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. Since the

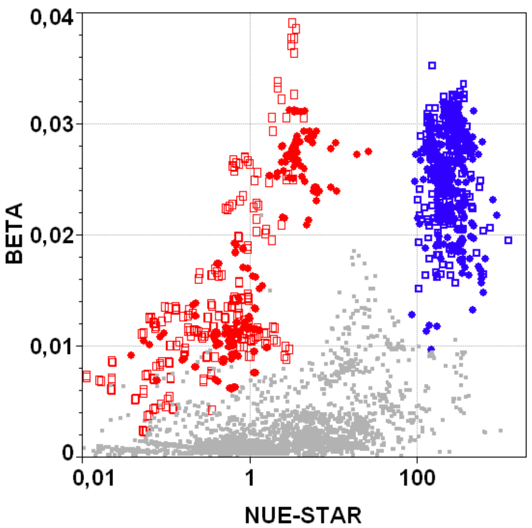

Fig.6 Range of ν_* of LHD and W7-AS high-β data. The data highlighted in blue represent the two W7-AS survey datasets. In red, the two datasets of LHD used for transport studies are shown (ISHCDB preliminary).

W7-AS high-β data are clustered in a high-collisionality region well separated from the LHD data (fig. 6), 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) was found in the high collisionality regime. Moreover, this survey indicates that LHD data even allow for a detailled 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 equilibrium and stability effects, MHD related data including configuration parameters, data characterizing the MHD mode activity, data on local pressure profiles and results of numerical equilibrium and stability calculations are foreseen to include in the ISHPD in a next step, in addition to data required for local transport studies.

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