Energy confinement of hydrogen and deuterium electron-root plasmas in the Large Helical Device

Felix Warmer¹,², H. Takahashi³,⁴, K. Tanaka¹, Y. Yoshimura¹, C. D. Beidler¹, B. Peterson¹,⁴, H. Igami¹, T. Ido¹, R. Seki¹, M. Nakata¹,⁴, M. Yokoyama³,⁴, T. Akiyama¹, H. Funaba¹, K. Ida¹, S. Kubo¹, A. Shimizu³, T. Shimozuma³, T. Tokuzawa¹, T. I. Tsujimura¹, H. Yamada³,⁴,⁵, I. Yamada¹, R. Yasuhara¹, M. Yoshinuma¹, S. Yoshimura¹, T. Morisaki¹,⁴, M. Osakabe¹,⁴ and The LHD Experiment Group

¹ Max Planck Institute for Plasma Physics, D-17491 Greifswald, Germany
² Fellow of the Alexander von Humboldt Foundation and the Japan Society for the Promotion of Science
³ National Institute for Fusion Science, National Institute for Natural Sciences, Toki, Japan
⁴ SOKENDAI (The Graduate University for Advanced Studies), Toki, Japan
⁵ Department of Advanced Energy, The University of Tokyo, Chiba, Japan

E-mail: Felix.Warmer@ipp.mpg.de

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Abstract

The dependence of the energy confinement and energy transport on the isotope mass is a long-standing open question in the stellarator community. With the recent upgrade of the Large Helical Device to allow for deuterium plasma operation, systematic isotope experiments could be carried out for the first time in a major non-axisymmetric device.

Within this framework, electron-cyclotron-resonance heated (ECRH) hydrogen and deuterium plasmas were investigated varying both density and heating power to establish a broad data set. Even at low power the central ECRH heating is sufficient to lead to stellarator-specific core-electron-root-confinement which features a peaked electron temperature profile and a positive radial electric field. For this data set, the energy confinement time and energy transport is investigated in detail and compared to the neoclassical theory.

Over the whole data set, the energy confinement time of deuterium is statistically 10%–20% larger than in hydrogen indicating that the ‘isotope effect’ also exists in non-axisymmetric devices. Both the electron and ion temperature are elevated in deuterium compared to hydrogen at the same effective absorbed power and density. From a neoclassical point-of-view, the electron-root and the positive electric field extend over nearly the entire plasma radius. Good agreement is found between the measured and theoretical neoclassical ambipolar electric field. The neoclassical energy-flux can account for up to half the experimental flux implying that turbulence is responsible for a significant fraction of the entire energy-flux.

*Author to whom any correspondence should be addressed.
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(Some figures may appear in colour only in the online journal)

1. Introduction

Compared to today’s experiments, which mostly employ hydrogen as a working gas, a fusion power plant will ultimately operate with deuterium and tritium to provide fusion power generation. It is therefore imperative to study the plasma behaviour in the context of such isotopic compositions. However, considering the scarce availability and half-life time of tritium, and in order to avoid a large number of energetic neutrons, the most practical approach to study isotope effects is to employ deuterium as working plasma species.

In fact, this practice has a long tradition in the fusion community and has been used extensively in many tokamak experiments to study isotopic dependencies [1–4]. One of the major interests in these studies has been the impact and scaling of the energy confinement time $\tau_E$ [5] on the isotope mass $M$. Any fusion power plant design is sensitive to the predicted energy confinement time [6] which critically affects the size of projected fusion reactors. Therefore, precise knowledge of the isotope effect is required to refine the design and size of future fusion power plants. This emphasises the importance of the isotope effect and our urge to understand it from a first principle physics.

The results obtained from tokamak experiments have so far been quite encouraging; generally, a confinement enhancement has been observed in both deuterium L-mode and H-mode plasmas with respect to identical hydrogen experiments. It was thus found that the confinement time scales positively with the isotope mass, $\tau_E \propto M^\alpha$ where $\alpha > 0$. However, the exact scaling has been found to vary among devices and depends on the experiment conditions (e.g. L/H-mode). Generally, the ratio of the deuterium to hydrogen confinement time varies between $1–1.5$, although some cases reported values up to $2$ [2]. An ‘average’ value is given by the ELMy H-mode energy confinement time scaling IPB98(y,2) as [7]:

$$\tau_{IPB98(y,2)} \propto M^{0.19}.$$  \hspace{1cm} (1)

It should be noted, however, that in some devices the confinement improvement is significantly larger than given by the scaling here. The improvement of confinement with the isotope mass is commonly and simply referred to as the ‘isotope effect’.

Despite the strong experimental evidence, a complete understanding of the isotope effect in tokamaks is still lacking [8]. It is generally agreed that the confinement improvement is related to turbulence through non-linear multiscale effects such as enhanced zonal flows, shear, and electro-magnetic effects leading to stabilisation of micro-instabilities. But the disentanglement of the related effects is still a challenge, thus remaining a contemporary topic of great relevance [9–11].

For stellarators, or helical devices in general, the situation is even less clear. In individual, well-diagnosed electron-cyclotron-resonance heated (ECRH) plasmas of the W7-AS experiment a confinement improvement of about $20\%$ was observed for deuterium plasmas compared to hydrogen [12]. However, the data in the international stellarator–heliotron confinement database did not give a clear dependence of $\tau_E$ on the isotopic mass. Consequently, the positive scaling found in isolated experiments could not be statistically reproduced in the stellarator-specific energy confinement time scalings ISS95 and ISS04 [13, 14]. It is for this reason that the existence of the isotope effect in stellarators and the dependence of the energy confinement on the isotope mass is, to date, an open question in the stellarator community.

Additional experimental data on this topic was a primary goal of the recent upgrade of the Large Helical Device (LHD) to employ deuterium as a plasma species [15, 16], thus allowing systematic isotope experiments for the first time in a major non-axisymmetric device. This experimental development has been accompanied by theory predictions based on gyrokinetic simulations in which it was generally found that in particular trapped-electron-modes (TEM) are more stable in a deuterium plasma at medium to high collisionalities consistent with tokamak simulations [17, 18]. At the same time, standard neoclassical theory predicts an increase of the neoclassical energy flux with isotope mass adding additional complexity to the isotope effect in stellarators.

Triggered by these developments and predictions in an attempt to disentangle neoclassical and turbulent contributions in isotopic plasmas, this work concentrates on ECRH plasmas (as the main heating source) in both hydrogen and deuterium. In stellarators, strong central ECRH heating leads to the emergence of the so-called ‘electron-root’, a stellarator-specific confinement regime characterised by highly peaked electron temperatures, flat ion temperatures and a strong positive radial electric field resulting from the ambipolarity condition to balance the neoclassical electron and ion particle fluxes [19, 20].

It may seem paradoxical to investigate the ion isotope effect on energy transport in ECRH plasmas which are dominated by the electron energy flux. However, as mentioned earlier, what is commonly and simply referred to as the ‘isotope effect’ is in reality a complex interplay of many different effects attributed to non-linear multiscale turbulence. Thus, as shown in [17, 18], electron transport can also be strongly affected by ion isotopes. Considering this, the electron-root regime serves as a good test-bed to study and validate neoclassical as well as turbulent transport effects in hydrogen and deuterium plasmas with the aim to contribute to clarifying the long-standing question of the isotope effect in stellarators. Complementary, high ion temperature deuterium plasmas with strong NBI heating
are described in [21]. Further, the formation of a strong e-ITB using co-ECCD and the reduction of $\chi_e$ in deuterium plasmas compared with hydrogen plasmas were also shown in [21] as initial results of the LHD deuterium campaign.

In section 2, an overview is given regarding the experimental setup, the achieved parameters and general characteristics of the obtained data set. In section 3, identical hydrogen and deuterium discharges are analysed in greater detail and compared to each other. Furthermore, the power balance and measured radial electric field are compared against the neoclassical theory. The global energy confinement and statistical difference between hydrogen and deuterium plasmas is presented in section 4 and a comparison with the ISS04 stellarator confinement scaling is undertaken. Finally, the main conclusions of this work are summarised in section 5 with a brief outlook.

2. Overview and overall properties of ECRH experiments

Before detailed experimental results and their analysis are presented, an overview is given in this section regarding the experimental setup and the general characteristics of the obtained data set.

2.1. Experimental setup

The LHD is the largest heliotron-type device in the world with a geometrical major radius of $R = 3.9$ m and a minor radius of $a = 0.6$ m. The LHD magnetic configuration consists of 10 field periods with a pole number of 2. The field is produced by two large helical field coils winding in a helix-like form around the torus supplemented by three sets of poloidal field coils to balance the vertical field. As the magnets are all superconducting, long-pulse or steady-state operation could potentially be realised.

This work makes use of the recent upgrades of LHD allowing both hydrogen and deuterium plasma experiments in the same operational campaign. For all the experiments considered here, the magnetic configuration was fixed to the slightly inward-shifted configuration which for LHD is commonly expressed in terms of the magnetic-axis position, here $R_{ax} = 3.6$ m. The average magnetic field strength on-axis was fixed to $B_{ax} = 2.75$ T.

All plasmas were fuelled by gas puffing with feedback-control in order to obtain similar line-averaged densities for both hydrogen and deuterium.

ECRH was employed as the main heating system. After a recent upgrade, LHD was equipped with six gyrotrons. Three gyrotrons with a working frequency of 77 GHz using O1-mode resonance, two gyrotrons with 154 GHz using X2-mode and one 82.7 GHz gyrotron. Each gyrotron has a power output of about $\sim$1 MW, except for the 82.7 GHz gyrotron with $\sim$0.27 MW. The microwaves are transmitted via corrugated waveguides with a transmission efficiency of 70–90%, thus amounting to a maximum of 5.4 MW port-through power which can be sustained for 1–2 s [22, 23]. The ECRH system was used for central power deposition, but at densities above $2 \cdot 10^{19}$ m$^{-3}$ the refraction from the 77 GHz gyrotrons cannot be neglected leading to slightly more off-axis deposition. When the density becomes higher than $3 \cdot 10^{19}$ m$^{-3}$, the one-path absorption of 77 GHz gyrotrons becomes very small. However, the shine-through power is reflected at the wall and can heat the plasma by second-path absorption. Thus, in respective higher density cases, the estimation of absorption and transport becomes more difficult. In addition, perpendicular NBI was used for CXRS measurements and NBI deposition was taken into account for the power balance analysis, which is presented later.

All data-sets used in this paper were obtained in the 19th LHD experimental campaign in 2017. During the campaign all inner vessel components remained identical, thus
allowing precise comparison between hydrogen and deuterium. Unfortunately, two gyrotrons were afflicted with technical problems during the campaign resulting in a maximum ECRH power of about 3 MW which could be used in the experiments. As a further consequence the ECRH injection, conditions were not exactly the same in hydrogen and deuterium. In deuterium, all gyrotrons were always set to the co-ECCD direction. On the other hand, in the hydrogen data set, one gyrotron was set to perpendicular-, one to co-ECCD and one to counter-ECCD injection. It has been observed that a strong variation between co-, balanced, or counter-injection can have an impact on the global confinement through e.g. core temperature flattening [24]. In the hydrogen data set used for the analysis in this paper, no core temperature flattening was observed. The hydrogen data has been checked for consistency with existing ECRH hydrogen experiment data from the 2014 experimental campaign. In addition, the data has also been checked with three hydrogen discharges obtained at the end of this campaign where all gyrotrons were set to co-ECCD. The data has been analysed in the same way as the 2017 data. No irregularities or discrepancies were found which affect the global confinement. Consequently, we argue that the different ECCD settings have no impact on the results obtained in this work. However, in future studies it should be clarified in detail how the use of ECCD affects the confinement and furthermore, if the ECCD has an impact on the isotope effect. For general comparison, in all figures a small data set with balanced ECCD will be shown for both hydrogen and deuterium. Since the detailed investigation of ECCD effects is beyond the scope of this work, the balanced ECCD data set will not be discussed here, but will be presented elsewhere.

In order to achieve steady-state-like conditions with thermal equilibrium, all the experiments were run for \( \sim 2 \) s which is sufficiently long compared with the energy

![Figure 2](image_url)

Figure 2. (a) Overview over the total stored kinetic energy \( W_{\text{kin}} \) within the ECRH data set as function of the product of the total absorbed power \( P_{\text{abs}} \) and line-averaged electron density \( \langle n_e \rangle \). (b) Corresponding energy confinement time \( \tau_E \) as function of the total absorbed power \( P_{\text{abs}} \) divided by the line-averaged electron density \( \langle n_e \rangle \).

confinement time in the range of \( \tau_E = 100–200 \) ms. For the systematic investigation of the isotope effect and comparison of hydrogen and deuterium plasmas, both the density and heating power were systematically and step-wise varied on a shot-to-shot basis. In this manner a large data set could be obtained spanning densities in the range 1–4.5 \( \times 10^{19} \) m\(^{-3} \) and powers of 1–3 MW. The successfully achieved parameter range is illustrated in figure 1, color-coded with the maximum electron temperature achieved in the steady-state phase of each experiment.

The white area shown in figure 1 at low power and high densities represents experiment conditions which could not be sustained, i.e. the heating power was not sufficient to sustain the respective high densities and corresponding radiation led to a radiation collapse of the discharge. It should be noted that the figure shows the gross ECRH power. Depending on the plasma parameters, the absorbed power is less than the gross power due to e.g. refraction effects.

The full radial electron temperature profile \( T_e \) has been measured with the Thomson scattering (TS) diagnostic with a time resolution of 10 Hz [25]. Since a technical problem of the TS optics led to asymmetric TS density profiles, the electron density was measured with the multi-channel far-infrared interferometer system (FIR) providing \( n_e \) profiles by Abel-inversion [26].

In order to measure the ion temperature profile \( T_i \) and the radial electric field profile at the edge, active charge-exchange-recombination-spectroscopy (CXRS) was employed [27] using perpendicular neutral-beam injection (NBI). To provide sufficiently high signal, the NBI power was set to 3 MW port-through power modulated with 80 ms on and 20 ms off. Despite this seemingly high power, the ECRH heated plasmas are nearly unaffected by the beams. For the low densities used in this work \( (n_e < 5 \times 10^{19} \) m\(^{-3} \)\), a large fraction of the NBI power is lost by shine-through and most of the remaining part
is removed by direct and trapped orbit losses. This is discussed in more detail in section 3.2 for the power balance.

In order to complement the measurement of the radial electric field \( E_r \) in the plasma centre, the heavy-ion-beam-probe (HIBP) diagnostic was employed. However, for a reasonable signal-to-noise ratio the measurements with HIBP are limited to \( n_e \leq 1 \cdot 10^{19} \text{ m}^{-3} \) [28].

The radiative power-losses from plasma impurities \( P_{\text{rad}} \) have been measured with the resistive bolometer camera system [29]. A radial emissivity and power loss profile is obtained by tomographic inversion assuming poloidal and toroidal symmetry.

The magnetic equilibrium mapping was determined by Thomson \( T_e \) mapping using TASK3D-a analysis suite [30].

### 2.2. Data set characteristics

In order to obtain sufficient statistics and characterise the experimental data set, all plasmas have been analysed at each available TS time point during the steady-state phase. The experiments were highly reproducible and thermal equilibrium is usually achieved within less than 800 ms after start-up. In the remaining steady-state phase, the time traces of density and temperature remain constant (see figure 3 as example).

One of the most important global parameters is the stored kinetic energy of the plasma which is calculated for each time point by integration of the temperature \( T_{n_a} \) and density \( n_{a} \) profiles and their summation over all occurring plasma species \( \alpha \) with \( \alpha = e, H, D, He, C \):

\[
W_{\text{kin}} = \frac{3}{2} \sum_{\alpha} \int V n_{\alpha} T_{\alpha} \, dV.
\]  

(2)

Generally, the plasmas which were obtained for this data set were quite pure and clean. The most prominent impurity in both hydrogen and deuterium plasmas was helium with a content between 5%–10%, while carbon was usually less than 1%.

The kinetic energy is closely related to the energy confinement time which is the focus of this work. To be able to assess the confinement time, however, the heating power absorbed by the plasma must be accurately known. For this reason, the total absorbed power is defined by the contributions from the central ECRH heating, the perpendicular NBI and losses by radiation as:

\[
P_{\text{abs}} = P_{\text{abs}}^{\text{ECRH}} + P_{\text{abs}}^{\text{NBI}} - P_{\text{rad}}.
\]  

(3)

For the calculation of the ECRH deposition and absorption the ray-tracing code LHDGauss has been used [31]. NBI contributions have been calculated by the FIT3D code. Both codes are part of the TASK3D-a analysis suite [30]. However, as FIT3D does not take into account orbit losses, the results from FIT3D greatly overestimate the deposited NBI power. In a more detailed analysis by comparing identical experiments with and without NBI it was found that only about 50% of the power calculated by FIT3D actually heats the plasma. Finally, the total radiation is taken from the bolometer diagnostic.

Given the stored kinetic energy and the total absorbed power by the plasma, the global energy confinement time can be calculated as:

\[
\tau_{E} = \frac{W_{\text{kin}}}{P_{\text{abs}} \cdot dW/dt}.
\]  

(4)

As the data points have been restricted to the steady-state phase, the time-dependent change \( dW/dt \) is very small.

The results of this global analysis are illustrated in figures (a) and (b). As expected from general scaling laws, the stored kinetic energy follows the product of heating power and density without much deviation or scatter \( W_{\text{kin}} \sim P^\gamma \cdot n^\delta \), \( \gamma, \delta > 0 \). Given the limited heating power and density range of the ECRH experiments, up to \( \sim 500 \text{ kJ} \) of stored kinetic energies are reached at maximum. It can be seen that the stored kinetic energy for deuterium plasmas is clearly above the stored energy for hydrogen plasmas over the whole range of power and density providing a first hint to a systematic difference between those isotopes.

The energy confinement time for the investigated experiments covers a broad range between 50–300 ms. Again, the data closely follows the general scaling behaviour \( \tau_{E} \sim P^\zeta \cdot n^\xi \), \( \zeta < 0, \xi > 0 \). To guide the eye, dashed lines with \( \xi = -\zeta = 0.6 \) are shown which provide boundaries for the parameter space. The confinement times of the deuterium plasmas clearly exceed the confinement times of the hydrogen
is closely matching for both cases

\[ n_e = 1 \cdot 10^{19} \text{ m}^{-3} \]

are elevated in the deuterium plasma.

\[ P_{\text{abs}} = \text{ECRH} \]

The selected discharges for the analysis presented here feature 3 MW of absorbed ECRH power and a line-averaged density of \( 1 \cdot 10^{19} \text{ m}^{-3} \). The low density was chosen to include measurements of the central radial electric field from the HIBP. Both the low density and high power ensure that the contributions from the modulated NBI are only marginally affecting the plasma.

The time traces for both the hydrogen and deuterium cases are shown overlayed in figure 3. The discharges have a duration of about 1–2 s and thermal equilibrium is reached after about 800 ms (the discharges start at \( t = 3 \) s). It can be seen that the central density \( n_e^0 \) is closely matching for both cases throughout the discharge. Still, both the central electron \( T_e^0 \) and ion temperature \( T_i^0 \) are elevated in the deuterium plasma compared with the hydrogen plasma. The measured diamagnetic energy \( W_{\text{diam}} \) is strongly influenced by the modulated NBI beam. In deuterium, the diamagnetic energy is higher which is most likely due to the higher beam energy; 60 and 80 keV both in deuterium compared to 40 keV in hydrogen.

The full profiles for both the hydrogen and deuterium case are overlayed in figure 4. As intended, the density is well matched and the electron density profiles have been chosen to be very similar for these cases. It should be noted, however, that the general data showed systematically more hollow density profiles in deuterium plasmas [32]. Although, not explicitly shown in cases presented here, this difference gives indication for different particle transport in hydrogen and deuterium. Similarly, also in both CHS and Heliotron J a qualitative difference was observed between hydrogen and deuterium particle transport [33, 34]. However, no clear conclusions can be drawn at this point and dedicated experiments are required to analyse the particle transport and balance. This is beyond the scope of this work but will be investigated in the future in more detail.

Given the matched density and absorbed ECRH power, the temperature difference becomes even more apparent when the full profiles are considered. Both electron and ion temperature are higher across the whole plasma radius in deuterium. In particular, in the centre of the plasma, where ECRH is deposited, the peaked electron temperature is not only higher, but the peaking region is also broader. The central peaking of the electron temperature is a typical feature of core-electron-root plasmas and seems to be more pronounced in deuterium. At the low density considered here, electrons and ions are nearly decoupled resulting in low ion temperatures with weak radial gradients. Considering the equipartition theorem, the coupling between deuterium and electrons should be worse than between hydrogen and electrons since the power transfer from electrons to ions scales inversely with ion mass

\[
P_{ei} \sim \frac{n_e \cdot (T_e - T_i)}{m_i \cdot T_e^{3/2}}. \tag{5}
\]

Thus, one would expect lower ion temperatures in deuterium. It is intriguing that the contrary is observed in these electron-root plasmas and it is thus indicated that transport effects dominate above the energy transfer from electrons to ions.

The detailed power balance will be investigated in the following in more detail.

3. Profile and transport characterisation of hydrogen and deuterium CERC plasmas

In an attempt to disentagle transport effects and more closely analyse the differences between hydrogen and deuterium plasmas, a pair of discharges with identical actuators is chosen and will be compared in the following. The identical actuators refer to the line-averaged density and the absorbed ECRH power. First, the time traces and profiles of the hydrogen and deuterium discharges will be compared followed by a detailed neoclassical analysis including the power balance and radial electric field.

3.1. Comparison of time traces and profiles

The selected discharges for the analysis presented here feature 3 MW of absorbed ECRH power and a line-averaged density of \( 1 \cdot 10^{19} \text{ m}^{-3} \). The low density was chosen to include

| Figure 4. Overlayed radial profiles of two identical \( (P_{\text{ECRH}} = 3 \text{ MW}, \langle n_e \rangle = 1 \cdot 10^{19} \text{ m}^{-3} ) \) hydrogen and deuterium experiments showing (a) electron and ion temperatures, (b) electron density and (c) electron pressure. |
|---|
| (a) Hydrogen \( (#132847) \) vs. Deuterium \( (#136370) \), \( t = 4s \) |
| (b) |
| (c) |
| | Overlayed radial profiles of two identical \( (P_{\text{ECRH}} = 3 \text{ MW}, \langle n_e \rangle = 1 \cdot 10^{19} \text{ m}^{-3} ) \) hydrogen and deuterium experiments showing (a) electron and ion temperatures, (b) electron density and (c) electron pressure. |
Figure 5. (a) Integrated absorbed power from ECRH heating (red), NBI (blue) as well as radiative power loss from impurities (grey). In black is the effective, total integrated power to the plasma representing the experimental energy flux for hydrogen and (b) for deuterium. (c) Neoclassical ion energy flux as calculated by DKES (grey) and GSRAKE (blue) as well as the total neoclassical energy flux (dashed red for DKES and solid red for GSRAKE) for hydrogen and (d) for deuterium. (e) Measured radial electric field with HIBP (light blue, centre) and CXRS (dark blue, edge) as well as neoclassical ambipolar electric field as calculated by DKES (black) and GSRAKE (red) for hydrogen and (f) deuterium. The light blue shaded area indicates the possible error with respect to the measurements.
3.2. Power balance, radial electric field and comparison to neoclassical theory

The representative pair of hydrogen and deuterium discharges selected in the last subsection is explored further here. The integrated radial profiles of the absorbed ECRH and NBI deposition power as well as the radiative power losses are illustrated in figures 5(a) for hydrogen and (b) for deuterium. The heating via ECRH leads to central deposition of the full ECRH power in contrast to the NBI. Due to the high shine-through of the perpendicular NBI, the power is mostly deposited in the edge region of the plasma with little influence on the core. In this case, shine-through and orbit losses reduce the absorbed NBI power to about 1 MW of the 3 MW port-through power. The radiation from impurities is mostly concentrated in the plasma edge $\rho > 0.7$ reaching about 1 MW total or 20%–30% of the total heating power.

Given the density and temperature profiles, the resulting neoclassical energy flux has been calculated to assess the importance of neoclassical and respectively turbulent transport in the presented scenario. Two different methods have been employed for the calculation of the neoclassical energy flux. The first method is the drift-kinetic-equation-solver...
(DKES) which solves the mono-energetic linearised drift kinetic equation as function of three dimensionless quantities (flux surface, collisionality, and $\mathbf{E} \times \mathbf{B}$ drift velocity) [35–37]. The transport coefficients are then easily obtained by an energy convolution over the Maxwell distribution. The second method employs the general-solution-of-the-ripple-averaged-kinetic-equation (GSRAKE) which does not rely on assumptions on the collision or poloidal precession frequency and includes both the $\mathbf{E} \times \mathbf{B}$ as well as the $\nabla \mathbf{V}$ term [38]. GSRAKE is, however, restricted to simpler magnetic fields which can be described by a multiple-helicity model [39]. This is the case for heliotron-type magnetic configurations such as LHD. Here, the most recent version of GSRAKE has been used which includes potential variations $\phi_1$ on the flux surface by requiring quasi-neutrality to be satisfied pointwise on a flux surface. The neoclassical ion and the total energy flux ($Q_\alpha = \Gamma_\alpha + \Gamma_{\alpha e}$) are given for both DKES and GSRAKE calculations in figures 5(c) for hydrogen and (d) for deuterium.

Due to the low ion temperatures, the neoclassical ion energy flux is vanishingly small in both hydrogen and deuterium. Under these conditions the total neoclassical energy flux is dominated by the neoclassical electron energy flux. The total energy flux from GSRAKE is in both cases somewhat larger than the ones calculated by DKES. This difference is due to the fact that GSRAKE includes the potential variation on a flux surface which generally leads to higher neoclassical particle and energy fluxes. Without $\phi_1$, GSRAKE results are in close agreement with the DKES results. Broadly speaking, in both hydrogen and deuterium the neoclassical transport can explain up to half the experimental energy flux across the whole radius. However, in deuterium the total neoclassical energy flux is larger compared to the hydrogen case by about $\sim 10\%$–$20\%$, in particular, in the centre of the plasma. This is partly due to the higher temperatures achieved in deuterium and partly due to the change of the collisionality from higher mass ions.

The measured radial electric field by HIBP (plasma centre) and CXRS (plasma edge) is shown in figures 5(e) for hydrogen and (f) for deuterium. The HIBP plasma potential measurements have a large error bar due to a generally low signal-to-noise ratio. Taking the radial gradient of potential measurements to obtain the radial electric field amplifies this error further. In order to obtain a reasonable profile a moving average in space and time has been used for the steady-state phase to reduce noise. The possible induced error from this procedure is indicated by the light blue shaded area. Similarly, the edge measurements by CXRS have been averaged over several time slices in the steady-state phase from 3.8–4.2 s to reduce the error. Both diagnostics together provide a full profile of the radial electric field.

Further, the neoclassical radial electric field has been calculated with both DKES and GSRAKE from the ambipolarity condition $\Gamma_e = \Gamma_i$ giving nearly the same result. Good agreement is found between the measured radial electric field and the neoclassical ambipolar radial electric field demonstrating the reliability of neoclassical theory for determining this quantity. Similar results have also been recently obtained in W7-X [40, 41].

This argument can be extended further. Given that the radial electric field can be explained by the non-ambipolar component of the neoclassical particle flux and given that the energy flux can only partly be explained by the neoclassical theory, it follows that the remaining particle flux must be intrinsically ambipolar. It can thus be speculated that turbulence-driven transport is responsible for a considerable fraction of the remaining energy flux, at least in terms of the conventional ordering of the gyrokinetic theory [42, 43]. This situation is quite different from tokamaks where the plasma can rotate freely and the turbulent Reynolds stress may affect the global electric field. This is, however, beyond the scope of this work and will be explored elsewhere.

The strongly peaked electron temperature profiles together with flat ion temperature profiles and a strong positive radial

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**Table 1.** Renormalisation factor of different data subgroups within the ISHCDB and their standard deviations, see [14].

| Device     | $f_{ren}$ |
|------------|-----------|
| TJ-II      | 0.25 ± 0.04 |
| Heliotron J| 0.58 ± 0.23 |
| W7-AS, $\epsilon_{2/3} < 0.48$ | 1.00 ± 0.27 |
| W7-AS, $\epsilon_{2/3} > 0.48$ | 0.79 ± 0.18 |
| LHD, $R_{ax} = 3.6$ m | 0.93 ± 0.15 |
| LHD, $R_{ax} = 3.75$ m | 0.67 ± 0.06 |
| LHD, $R_{ax} = 3.9$ m | 0.48 ± 0.05 |

**Table 2.** Parameters of the LHD, $R_{ax} = 3.6$ m magnetic configuration, as defined in the ISS04 scaling where $R, a, B_T$ and $\epsilon_{2/3}$ are the major radius, minor radius, magnetic field and the rotational transform at $r/a = 2/3$. Note that in this case the magnetic field $B_T$ is defined by the total toroidal flux enclosed within the last closed flux surface (LCFS) divided by the area of the LCFS.

| Parameter | Value |
|-----------|-------|
| LHD, $R_{ax} = 3.6$ m |  |
| $R$ (m) | 3.684 |
| $a$ (m) | 0.634 |
| $B_T$ (T) | 2.42 |
| $\epsilon_{2/3}$ | 0.65 |

**Figure 8.** Confinement times of LHD electron-root plasmas in hydrogen (blue) and deuterium (red) as function of their expected values from the ISS04 scaling.
electric field are well known features of the stellarator-specific core-electron-root-confinement regime (CERC) [19, 20]. The strong positive radial electric field brings the neoclassical electron energy transport down from the unfavourable \( 1/\nu \) regime to the \( \sqrt{\nu} \) regime. In this case the effective helical ripple \( \epsilon_{\text{eff}} \) does not directly enter the scaling of the transport coefficients which in the \( \sqrt{\nu} \) regime scale as \( D_{\sqrt{\nu}} \sim n^{-1/2} T_5^{3/4} |\Omega_0|^{-3/2} \) with \( \Omega_E = E_x/rB_0 \) being the poloidal rotation frequency.

3.3. Anomalous part of the heat conductivity

The calculation of the neoclassical energy flux allows to also investigate the remaining energy flux, which here will be referred to as anomalous energy flux \( Q_{\text{ano}} \). The anomalous energy flux for the electrons and background ions is obtained by subtracting the neoclassical energy flux from the power source terms and taking into account the power transfer between electrons and ions. Radiation and charge-exchange losses are neglected in this analysis since the simulations cover only \( \rho < 0.8 \).

\[
Q_{\text{ano}}^e = P_{\text{NBI}}^e + P_{\text{ECRH}}^e - P_{\text{ei}} - Q_{\text{NC}}^e \quad (6)
\]

\[
Q_{\text{ano}}^i = P_{\text{NBI}}^i + P_{\text{ei}} - Q_{\text{NC}}^i \quad (7)
\]

An effective anomalous heat conductivity can then be simply defined by

\[
\langle \chi_{\alpha}^{\text{ano}} \rangle = \frac{Q_{\text{ano}}^\alpha}{n_\alpha \nu_\alpha T_\alpha} \quad (8)
\]

where \( \alpha = e, i \) for electrons and ions, respectively.

The results are shown in figure 6. It can be seen that the anomalous heat conductivity is higher in hydrogen for both electrons and ions, in particular in the plasma region around \( \rho \approx 0.3-0.6 \). This result gives an indication that the anomalous transport/turbulence is reduced in this plasma region.

No clear conclusion can be drawn for the plasma centre. The plasma volume for plasma centre layers is very small such that already small errors significantly influence the calculations. The numerical resolution and accuracy for the central plasma region is not sufficient to give clear values for the effective heat conductivity. Further, the very plasma edge \( (\rho > 0.8) \) needs to be treated with care. As already mentioned, charge-exchange has been neglected here, which can act as an additional loss channel at the plasma edge. An accurate neutral gas density profile would be required for a more detailed assessment of CX-losses.

4. Energy confinement in the greater picture

In order to bring the obtained results into broader context, the calculated confinement times are compared with values given by the stellarator confinement time scaling ISS04 including their respective renormalisation factor, see table 1. This is illustrated in figure 7 overlayed with data points from other stellarators as documented in the international stellarator–heliotron confinement database (ISHCDB) [44]. The geometric parameters for the \( R_m = 3.6 \) m configuration as defined in the ISS04 scaling are given in table 2.

In context of the existing data in the ISHCDB it can be seen that the confinement times obtained here for LHD electron-root plasmas are among the highest energy confinement times so far documented. For this data set a renormalisation factor of 0.93 has been used according with the \( K_{\text{ax}} \) = 3.6 m magnetic configuration. This is one of the highest values compared with other data subgroups in the ISHCDB. The maximum value of \( f_{\text{ren}} = 1 \) was defined by high performance W7-AS experiments. The data shown here from the ISHCDB has been obtained before 2004 and the respective scatter is large compared to the high-quality data presented here for LHD electron-root plasmas.

A more detailed view on the confinement times obtained for the data set in question here is illustrated in figure 8 where the figure has been zoomed on the relevant range. It can be clearly seen in figure 8 that deuterium electron-root plasmas show improved confinement compared to hydrogen plasmas across the whole parameter range covered in this data set. Statistically, the energy confinement in deuterium improves by 10%–20% which is a first indication of an existing positive isotope effect in stellarator/heliotron devices. As the neoclassical transport increases with deuterium as a plasma species, it can be concluded that the improved confinement must result from reduction of other transport channels such as turbulence. This was characterised in the last section with the reduction of the anomalous heat conductivity in deuterium compared with hydrogen.

Generalised gyrokinetic simulations predict, for example, that TEM are more stable in medium to high collisionality deuterium plasmas [17, 18]. However, in order to check if such statements could be used as explanation for the case here, detailed non-linear gyrokinetic simulations are necessary using the obtained experimental profiles and gradients. In the meantime, linear gyrokinetic simulations have been started employing the experimental profiles of high-\( T_e \) plasmas supporting the presented results [45].

Further, in an attempt to compare the data set with the ISS04 scaling a non-linear regression of the form

\[
\tau_{\text{E}}^{\text{reg}} \sim P_{\text{el}}^{\alpha} \cdot \nu_\alpha^{\beta} \cdot M_{\text{om}}^{\gamma} \quad (9)
\]

has been carried out for the hydrogen and deuterium data set separately as well as for the combined data set to obtain the mass dependence \( \alpha_{\text{m}} \). The results are given in table 3.

While the density dependence is nearly identical for all cases, some deviation can be recognised for the power dependence. The power dependence for the hydrogen data set is similar to the ISS04 scaling, but the results from the deuterium regression deviate and give a smaller value. It is not clear if this is a particular deuterium effect or due to large scatter in the deuterium data since the coefficient of determination \( R^2 \) for the deuterium regression is with 0.785 much worse than the one for the hydrogen data set with 0.985. More data over a wider parameter space needs to be obtained to give a clearer answer about the power dependence. However, the result for the mass dependence for the combined data set is quite robust resulting in

\[
\tau_{\text{E}}^{\text{reg}} \sim M^{0.26 \pm 0.03}. \quad (10)
\]
Table 3. Results from the non-linear regression analysis of the presented hydrogen and deuterium data set, as well as their combination to obtain the mass dependence. The coefficient of determination $R^2$ is 0.985, 0.785 and 0.826, respectively.

| Data set     | $\alpha_p$  | $\alpha_n$ | $\alpha_M$ |
|--------------|-------------|------------|------------|
| Hydrogen     | $-0.58 \pm 0.03$ | $0.64 \pm 0.01$ | ---        |
| Deuterium    | $-0.38 \pm 0.03$ | $0.61 \pm 0.03$ | ---        |
| Combined     | $-0.39 \pm 0.03$ | $0.61 \pm 0.02$ | $0.26 \pm 0.03$ |
| ISS04        | $-0.61 \pm 0.01$ | $0.54 \pm 0.01$ | ---        |

Statistically, this gives a strong indication for the existence of an isotope effect in non-axisymmetric devices. But further confirmation in the next experimental campaigns should be considered with more detailed analysis before a final conclusion can be made.

4.1. Discussion

The scaling of the energy confinement time is an important, yet contentious topic in the magnetic fusion community. Generally, confinement time scalings allow the comparison of different devices, transport regimes or magnetic configurations by a set of reduced global parameters following a simple power law dependence. For example, in the ISS04 scaling, subsets in the data were identified which showed an offset with respect to each other despite following the same power law dependence. This offset has been expressed by the so-called renormalisation factor $f_{ren}$, see table 1. This renormalisation factor is considered to represent the confinement improvement/degradation based on the properties of the magnetic configuration. However, so far, this could not be physically explained and it is unclear if neoclassical or turbulent transport effects are affected most. It should also be noted that the scatter of the data points in the ISHCDB is quite large, much larger than for tokamaks. Thus the ISS04 scaling and its predictive values need to be used with care [6]. This also applies when new experimental data is compared to the scaling as is done in this work.

As can be seen in figure 8, both hydrogen and deuterium experiments seem to deviate from the scaling for small confinement times, while experimental confinement times seem to approach the ISS04 scaling at higher confinement time regimes. Considering that the confinement times obtained in this work are substantially higher than the existing values in the database means that the values here are beyond the parameter range in which the ISS04 was derived. Consequently, the comparison given in figure 8 can only be considered as qualitative. For a more quantitative assessment, the parameter range of the electron-root experiments needs to be extended including higher heating power and density. Further, for comparison also experimental data under ion-root conditions needs to be obtained as well as data from NBI heated plasmas.

Generally, the definition of the global energy confinement time can be misleading. As can be seen in figure 5, the power input from the modulated NBI is mostly deposited at the far edge. Consequently, the power from the NBI does not effectively heat the plasma, but by definition, the integrated power value from NBI is included in the calculation of the global energy confinement time; see equations (3) and (4). Therefore, the inclusion of the NBI power artificially reduces the confinement time presented in this work. For comparison, the analysis of pure ECRH experiments without NBI modulation leads to about $\sim 20\%$ higher confinement times, as shown in [32]. Thus, global energy confinement times need to be discussed with care taking into account profile effects which can strongly affect global parameters.

5. Conclusions and outlook

The dependence of the energy confinement and energy transport on the isotope mass is a long-standing open question in the stellarator community. With the recent upgrade of the LHD to allow for deuterium plasma operation, systematic isotope experiments could be carried out for the first time in a major non-axisymmetric device. Within this framework, ECRH hydrogen and deuterium plasmas were investigated varying both density ($1 \cdot 10^{19} \text{ m}^{-3}$) and heating power (1–3 MW) to establish a broad data set. Stored kinetic energies up to 500 kJ were achieved with a confinement time in the range of 100–200 ms. The central ECRH heating leads, in all cases, to the stellarator-specific electron-root feature which exhibits a peaked electron temperature profile, a flat ion temperature profile and a positive radial electric field.

A comparison of a hydrogen and deuterium case with nearly identical heating power and similar density was performed. The deuterium case showed elevated temperature profiles in comparison with the hydrogen case. In particular, the electron temperature was not only higher, but the peaking region also broader. Intriguing is the increased ion temperature in deuterium. From the equipartition theorem one would expect lower ion temperatures in deuterium due to the reduced coupling between electrons and ions, however the contrary is observed. It is thus indicated that transport effects dominate above the energy transfer from electrons to ions.

Neoclassical analysis of these cases showed that about half the energy flux can be explained by neoclassical theory which is nearly completely dominated by the electron energy flux in these CERC plasmas. However, in deuterium the neoclassical energy flux is about 20% higher than in hydrogen due to higher temperatures. Good agreement is found between the measured radial electric field and the neoclassical ambipolar radial electric field demonstrating the reliability of the neoclassical theory for determining this quantity. Considering that the radial electric field can be explained by enforcing the ambipolarity condition on the neoclassical particle flux it can be argued that the remaining energy flux is caused by intrinsically ambipolar turbulence. Since the neoclassical energy flux is higher in deuterium despite the higher temperatures and confinement, it follows that the remaining energy flux, i.e. turbulence, must be reduced in deuterium plasmas. This is illustrated by the calculation of an effective anomalous heat conductivity which is lower in deuterium than in hydrogen. This argument is qualitatively consistent with generalised
gyrokinetic simulations which predict that TEMs are more stable in medium to high collisionality deuterium plasmas. However, more detailed non-linear gyrokinetic simulations with the obtained experimental profiles and gradients are required to further validate this statement.

Statistically, the energy confinement is 10%–20% higher in deuterium compared with hydrogen over the whole experimental data set indicating the existence of the isotope effect in helical devices in the analysed data set. Further, the obtained experimental confinement times are close to the ISS04 confinement time scaling. However, the confinement times substantially exceed the values in the existing ISHCDB data set. The comparison with the ISS04 scaling must be therefore considered to be of a more qualitative nature. For a closer, more quantitative assessment the experimental parameter range must be extended with higher heating power and density. Further data in the in-ion-root regime needs to be included as well as data from NBI plasmas. This work can, therefore, only be considered as a starting point of a more thorough investigation of the isotope effect and energy confinement of hydrogen and deuterium plasmas.

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ORCID iDs

Felix Warmer https://orcid.org/0000-0001-9585-5201
Y. Yoshimura https://orcid.org/0000-0001-6744-1829
C.D. Beidler https://orcid.org/0000-0002-4395-239X
M. Nakata https://orcid.org/0000-0003-2693-4859
K. Ida https://orcid.org/0000-0002-0585-4561
S. Yoshimura https://orcid.org/0000-0002-0602-0665

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