Penetration studies for deuterium pellets in W7-AS

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Abstract
Deep particle fuelling into a fusion relevant plasma can be performed by the injection of cryogenic hydrogen or deuterium pellets. However, the penetration depth and fuelling efficiency can be strongly limited for the case, that enhanced pellet ablation by fast particles occurs. By now, only a limited database exists for the penetration depth of ice pellets into stellarators. To fill this gap to some extent, the penetration depth is measured during pellet injection into purely Electron Cyclotron Resonance Heated (ECRH) plasmas on the stellarator W7-AS. These data are compared to the International Pellet Ablation Database (IPADBASE) [1]. Good agreement is found, if the Neutral Gas Shielding model (NGS) [10] is applied for the scaling law of the penetration depth. The experimental data from W7-AS are used as the basis for the planning of a new pellet injection system for the stellarator W7-X, which is presently under construction.

Introduction and motivation
In order to predict the fuelling efficiency and the penetration depth during pellet injection into a fusion relevant plasma, it is essential to have an experimental database which describes these quantities as a function of the background plasma parameters. The experimental database can be supported by numerical studies of the ablation process. They have to take into account the impact of the background plasma particle and heat flux on the pellet, but also the contribution of fast particles, which are induced by the plasma heating [2]. This turns out to be a complicated task, because a complex interaction is observed between the pellet ice, the already ablated material from the pellet surface and the background plasma particles. In particular, the available heat reservoir for the ablation is partly determined by the magnetic field topology, which can be rather complicated in a stellarator.

Pellet injection experiments are performed in the advanced stellarator W7-AS [3]. This is done for purely ECRH heated plasmas, which are characterised by relatively low electron densities \( n_e \) below \( 10^{20} \, \text{m}^{-3} \) and high electron temperatures \( T_e \approx 1-3 \, \text{keV} \). In addition to the heat flux, which is carried predominantly by the thermal electrons to the pellet, a contribution from suprathermal electrons has to be considered, which are produced by ECRH. Enhanced ablation of the pellet by those highly energetic electrons can considerably reduce the penetration depth.

The stellarator W7-AS consists of five almost linear modules shaped as a pentagon, according to \( m = 5 \) toroidal field periods. In the five corners the magnetic field strength \( B \) can be varied by a variation of the electric current in the field coils. The pellets are injected
almost in the middle of one module. The ECRH power is applied locally into one of the corners.

For the experiments, the "standard configuration" is compared to a "ripple configuration", both with on-axis and off-axis power deposition. In the "standard configuration", a magnetic minimum ($B = 2.49$ T) is located in the corners in comparison to a mean $B = 2.52$ T around the torus on the magnetic axis. Thus, the ECRH resonance ($f = 140$ GHz, X-mode launch) is close to the magnetic axis, providing on-axis deposition. The mean $B$ can be lowered to $B = 2.40$ T in the corners in the "standard configuration", providing ECRH off-axis deposition. In the "ripple configuration", a magnetic maximum is applied in the corners with $B = 2.50$ T in comparison to a mean $B = 2.44$ T around the torus on the magnetic axis. The X-mode heating applies momentum to the electrons mainly in the perpendicular direction, and produces therefore suprathermal electrons [9]. Thus, in the "standard configuration" the suprathermal electron population is located in the ECRH launching plane and remains to some extent trapped at this location, while in the "ripple configuration" they can drift freely in the toroidal direction. In this very simplified consideration, one expects therefore a higher fraction of highly energetic electrons in the "ripple configuration" in comparison to the "standard configuration" at the location of the pellet launch.

This situation is shown in fig. 1. Mod(B) is given as a function of the toroidal angle for the different configurations, together with the locations of the ECRH launch and the pellet injection. One corner of the pentagon is located at 36 degrees. Note that the pellet injection port is not really in the same module as the ECRH launch as shown simplified in the graph (26 degrees away from ECRH to the left), but it is 98 degrees away from ECRH to the right. But this plays no role for statements made here.

The pellet injection experiments are performed for different magnetic configurations, as well as for a variation of the heating power and the background n_e. Some Neutral Beam Injection (NBI) heated discharges are referenced to for comparison. The pellets are of cylindrical shape with a diameter of 1 mm and a mean length of 1 mm, corresponding to a

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particle content of $\approx 3 \cdot 10^{19}$. Slight variations of the pellet length during the ice production from pellet to pellet provide the variation of the pellet mass as shown in the data below. The pellet velocity is $\approx 500$ m/sec. The pellets are produced and accelerated by a pipe gun system, which was constructed by the Oak Ridge National Laboratory ORNL, and which was loaned to IPP for pellet experiments. The pellet mass is measured by a microwave cavity oscillator. The pellet velocity is determined by a fast light barrier system. The pellet ablation cloud is recorded by a standard video photographic system, which allows for the determination of the pellet penetration depth directly from the photographs. The electron density is measured by a microwave interferometer, the electron temperature by an Electron Cyclotron Emission system.

The injection of pellets into purely ECRH heated discharges is of particular interest for the future stellarator experiment W7-X [4], which is currently under construction in Greifswald, Germany. W7-X will be fully optimised with respect to confinement properties and stability, and a minimisation of the internal plasma currents. For this device, long discharges (up to 30 minutes) with ECRH only can be performed. Central particle fuelling is possible with additional NBI heating. However, the injectors can provide only pulses with a duration of $\approx 10$ sec, with $\approx 5$ minutes cooling time between subsequent pulses. Neoclassical transport calculations have been performed to study the impact of the drift optimisation on the particle and heat transport [5]. For the case of well-localised on-axis deposition of the ECRH power, for some of the possible magnetic configurations an outward directed particle pinch term is predicted. This is driven by the $T_e$ gradient. The neoclassical particle confinement time at outer radii can largely exceed the energy confinement time. As a result, extremely hollow density profiles together with centrally peaked $T_e$ profiles are predicted, which could eventually approach the stability criterion for resistive interchange mode activity. This could degrade the global discharge confinement considerably.

One possibility to avoid this unfavourable scenario is central particle fuelling. This could be attained with pellet injection. Therefore, the investigation of the ablation process during purely ECRH heated discharges in W7-AS is an important preparation for any pellet fuelling activity on W7-X. This includes the pellet injection technique, as well as the question about a reliable scaling law for the penetration depth.

This leads directly to a fundamental difficulty, which is sketched now briefly. The following input data are used: a central $T_e = 3$ keV, for $n_e(0) = 8 \cdot 10^{19}$ m$^{-3}$ the plasma particle content is $50 \cdot 10^{20}$ protons, the distance between the plasma edge and the magnetic axis is $\approx 45$ cm at the pellet injection port, the pellet velocity 1000 m/sec. Then, a central particle fuelling of $\approx 10^{20}$ atoms per MWatt heating power will be required to maintain stable discharge conditions. The total ECRH heating power can be up to 10 MW.

Table I shows the pellet radius, the particle content and the calculated penetration depth, if the NGS scaling law is employed [8]. To penetrate close to the magnetic axis (corresponding to a penetration depth of $\approx 45$ cm), the pellet size has to be at least 2.5 - 3 mm. But then the content is more than $40 \cdot 10^{20}$ atoms, which will roughly double the
electron density of W7-X for the parameters given above. This is then higher than the ECRH cutoff density of \( n_e \approx 1.2 \times 10^{20} \, \text{m}^{-3} \), and it is much more than the required particle fuelling rate for 10 MW ECRH heating power, if a feeding rate of 1 pellet per second is assumed. Simply applying large pellets is therefore not enough.

<table>
<thead>
<tr>
<th>Pellet radius [mm]</th>
<th>Particle content ([10^{20} , \text{Atoms}])</th>
<th>Penetration depth [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.5</td>
<td>23</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>34</td>
</tr>
<tr>
<td>2.5</td>
<td>40</td>
<td>39</td>
</tr>
<tr>
<td>3</td>
<td>70</td>
<td>45</td>
</tr>
</tbody>
</table>

*Table 1. Pellet penetration depth and particle content for different pellet radii.*

Probably a sophisticated pellet injection program has to be developed, with a combination of small and fast pellets at a high repetition rate, and simultaneously larger and slower pellets at a low repetition frequency. Even a feedback-controlled system might be envisaged, which meets the requirement of combined central fuelling with a relatively small fuelling rate.

**Results**

When looking at the video photographs of the pellet ablation clouds [6], no significant difference between ECRH and NBI discharges can be observed. During ECRH heating, the striations are not so pronounced as with NBI, but still visible. A strongly enhanced ablation and a significantly reduced penetration depth due to suprathermal electrons during ECRH could not be observed. This holds regardless of the ECRH heating power or the background electron density.

The fuelling efficiency is always better than 50%, if this is defined as the ratio between the particle contents of the pellet, and the particles deposited in the plasma. This holds almost regardless of the chosen heating method. In fig. 2 is shown the measured particle fuelling efficiency versus the central \( T_e \) before the pellet injection. The electron temperature is chosen, because the NGS model predicts the strongest influence of this parameter on the penetration. Due to the small amount of data, no significant differences are observed between the three scenarios: on-axis (open circles), off-axis ECRH (dots) into the "standard configuration", and on-axis ECRH into the "ripple configuration" (+). However, in the mean the fuelling efficiency is smallest for the "ripple configuration" (≈ 60%). This might indicate some influence of drifting suprathermal electrons, produced by ECRH, which arrive at the pellet injection location, opposite to the standard configuration. Linear regressions to the data (linear lines) highlight the trend for higher electron temperatures: the higher \( T_e \) the smaller is the fuelling efficiency. This appears as reasonable if the enhanced ablation due to the background thermal electrons is considered. For the highest
$T_e \approx 3$ keV all heating scenario and magnetic configurations merge into the same fuelling efficiency $\approx 60\%$, possibly indicating that the impact of the suprathermal electrons recedes in comparison to the thermal electron population.

Some examples lie above 100% due to the measurement uncertainty. They are "cut down" to reasonable 100% for the plot. For NBI heated discharges, the database available is too poor to be included in the plot. Any dependencies between the fuelling efficiency and other plasma parameters (instead $T_e$) are less pronounced than those, which are shown in fig. 2.

In a few examples, density peaking could be observed after pellet injection. However, the relative change in the peaking factor $P = n_e(0)/\bar{n}_e$ is always $< 10\%$. One example of the density profile development is shown in fig. 3, which was taken during high-density experiments with NBI. The peaking factor increases by 6%, mainly the central density increases after pellet injection. The edge channels remain constant. The pellet particle content was $4.3 \cdot 10^{19}$ particles, 25 msec after the pellet injection about $2.8 \cdot 10^{19}$ particles were deposited in the plasma, corresponding to a fuelling efficiency of 65%. Due to the relatively small change in the density peaking, no significant enhancement of the global energy confinement time $\tau_E$ could be observed. Before and after the pellet injection, only the predicted density dependency $\tau_E \propto n_e^{0.5}$ for representative discharges in W7-AS could be confirmed [7]. This behaviour is typical for pellet injection into W7-AS.

There is a certain tendency for larger pellets to increase the peaking factor more considerably. However, this effect is not very pronounced and statistically not significant.

Next, the measured pellet penetration depth in W7-AS is compared to a scaling law, derived for a NGS model, and for measured depths as derived for representative discharges from several tokamaks. Those had been collected for the pellet penetration database IPADBASE [1]. However, it is emphasised that the W7-AS data include ECRH

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**Fig. 2. Particle fuelling efficiency (%) versus central electron temperature for three different heating methods. The linear lines show fits to the data.**

![Graph showing particle fuelling efficiency vs. electron temperature for different heating methods.](image-url)

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discharges, in opposite to the IPADBASE data collection, where ECRH and Lower Hybrid (LH) shots are excluded because of the highly energetic particles.

For the comparison shown here, we employ the scaling law for the NGS model, which does not deviate strongly from the experimental tokamak database for auxiliary heated discharges. The result is shown in fig. 4. Along the x-axis is shown the expected penetration depth according to NGS, along the y-axis the measured penetration depth into W7-AS discharges. Different heating methods or magnetic configurations are encoded by different symbols. Here, we distinguish between ECRH on-axis into the "standard configuration" (open circles), ECRH off-axis into the "standard configuration" (dots), ECRH on-axis into the "ripple configuration" (+ signs), and NBI heating (squares). For the NBI discharges, in general the electron densities were considerably larger ($n_e(0) > 2 \cdot 10^{20}$ m$^{-3}$) than for all ECRH discharges ($n_e(0) < 1 \cdot 10^{20}$ m$^{-3}$). For all discharge scenario, variations of the background density and the heating power were performed. Lambda denotes the penetration depth, $a$ is the minor plasma radius.

Fig 3: Electron density profiles 25 msec before (dots) and after (squares) pellet injection. The curves give parabolic fits to the measured data to guide the eye.

Fig 4: Expected pellet penetration depth according to the NGS model versus the measured penetration depth in W7-AS for different heating methods and magnetic configurations.
Obviously, the majority of the W7-AS discharges can be described quite well with the NGS scaling law. The expected and the measured penetration depths agree well (as denoted as the diagonal line in the plot). From this we conclude that the suprathermal electrons play no significant role for the ablation and the penetration depth in W7-AS. This is consistent to the observation, that the striation behaviour is not strongly influenced by the heating method or the magnetic configuration, and the possible presence of fast particles.

But for about 25 examples, the measured penetration exceeds the expected one from the scaling law. For all heating methods applied, and for all magnetic configurations such examples can be observed. This leads to the conclusion that neither the heating nor the configuration is decisive for this enhanced penetration, but another mechanism.

A possible explanation for that behaviour is illustrated in fig. 5. Here, the absolute deviation between the measured and the scaled penetration depth is plotted versus the central electron temperature of the background plasma. It becomes obvious that two groups of examples exist. The first one (denoted as I) shows a small deviation. All members of this group can be described by the NGS scaling law. But the second group (denoted as II) deviates from the NGS scaling law. They penetrate much deeper than predicted by the scaling law. All members of group II belong to discharges with very low electron temperatures smaller than about 800 eV. Obviously, only for very low $T_e$ deviations from the scaling law might occur. The existence of group II can be understood from the fact, that here the factor $(\lambda/a)$ reaches one. For those cases, the pellets cross the magnetic axis. But after they crossed it, they experience only already cooled plasma, an effect that enhances the penetration depth further. However, examples with such low $T_e$ had also been realised for the data input for IPADBASE. This leads to the assumption that the enhanced penetration for low $T_e$ is a peculiarity of W7-AS, which is a comparably small stellarator in contrast to the relatively large tokamaks taken into account for the IPADBASE data collection. In W7-AS, the pellets can easily reach the magnetic axis, in opposite to larger plasma devices. The small machine size might therefore be a good explanation for the enhanced penetration during low $T_e$ discharges.
Thus, it is concluded that the NGS scaling law describes quite well the penetration depth of pellets, not only for tokamaks but also for W7-AS discharges. Only for "cold" discharges with a central $T_e$ considerably below $\approx 1$ keV the experiments tend to deviate from the NGS model. This confirms the approach for W7-X, to employ the NGS scaling law for the prediction of the pellet penetration depth. The pellet database, as well as the derived scaling law, is a good tool to prepare the concept and design for the future pellet injectors to be used on W7-X. And the aspects of pellet injection physics into a large stellarator can be considered in advance.

[8] W.A. Houlberg, S.E. Attenberger, private communication