Magnetic Field Dependence of Pellet Penetration

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Injection of cryogenic hydrogen isotope pellets into fusion plasmas is presently the main fuelling method and an established ELM control method foreseen for the ITER device. In both cases pellet penetration depth and the resulting deposition profiles are the key parameters as the large fuelling pellets have to penetrate beyond the pedestal region for effective core fuelling, whereas small ELM pacing pellets have to reach about the pedestal top for the prompt ELM triggering mechanism to take place [1].

To challenge present ablation theories, an empirical penetration-depth scaling has been established at ASDEX Upgrade (AUG) based on the high-field-side pellet ablation database (HFS-PAD, 509 pellets) by a new approach using statistical methods [2]. Contrary to empirical scalings with theory based variable selection, in this study the variables to be included in the scaling were selected from eight plasma and two pellet parameters based on their statistical importance in the penetration depth (λ) determined through model selection analysis. The comparison of the empirical results to two theoretical pellet ablation theories (simulations performed using on AUG density and temperature profiles), the neutral gas shielding model (NGS) [3] and the hybrid pellet ablation model [4] is shown in Table 1.

Theory based scaling: $\lambda / a = C \cdot m_p^{\alpha_1} \cdot v_p^{\alpha_2} \cdot T_e^{\alpha_3} \cdot n_e^{\alpha_4}$

Empirical statistical scaling: $\lambda / a = C \cdot m_p^{\beta_1} \cdot \tilde{v}_p^{\beta_2 + \beta_3 \cdot \ln \tilde{v}_p} \cdot \overline{T}_e^{\beta_4} \cdot B_t^{\beta_5} \cdot \kappa^{\beta_6}$

No.	Exponents	C	m_p	$v_p^{I.}$	$\tilde{v}_p^{II.a}$	$\tilde{v}_p^{II.b}$	$\overline{T}_e$	$\overline{n}_e$	B_t	κ
1	NGS Model	0.018	0.30	0.49			-0.71	-0.15		
2	Hybrid Code	0.031	0.35	0.41			-0.69	-0.18		
3	**HFS Scaling**	**0.25**	**0.22**		**0.24**	**-0.34**	**-0.67**		**-0.41**	**1.28**
	(Std. dev.)	(0.04)	(0.02)		(0.03)	(0.05)	(0.04)		(0.08)	(0.31)

Table 1. Comparison of the derived empirical penetration-depth scaling based on statistical model selection analysis of ASDEX Upgrade data to the theoretical models, as derived in [2].

Regarding the electron temperature (T_e), pellet mass (m_p) and velocity (v_p) reasonable agreement was found between the empirical and theoretical scalings. The main differences found were the absence of an electron density (n_e) dependence as already indicated in [5] and inclusion of two additional variables, the magnetic field (B_t) and a geometrical factor, the elongation (κ). For ITER and future plasma devices the elongation is not expected to be substantially different from κ=1.7, as in many present day devices. On the other hand, the magnetic field in ITER will approximately double its value to 5.3 T with respect to the standard 2.5 T of AUG. Thus the magnetic field dependence can affect the extrapolations and needs further exploration.

Although not included in previous scalings, the magnetic field is still of importance in the ablation process through the following considerations. First, the ablation rate and therefore the penetration depth also depend on the cross-field extent of the cloud. The cross-field expansion of the pellet cloud is stopped when ionization sets in at the cloud periphery [6]. How fast this trapping of the cloud occurs depends on the cloud parameters as well as the strength of the magnetic field determining the cross-field extent of the cloud. A stronger compression of the pellet cloud, would however (through the higher shielding, thus lower ablation rate) result in slightly positive magnetic field dependence contrary to the empirical results. On the other hand, drift effects transporting the ablatant material inward, i.e. toward the plasma center also depend on the gradient strength of the magnetic field.

In order to study the magnitude and direction of this effect, dedicated experiments have been carried out at ASDEX Upgrade to provide single parameter scans for the magnetic field and electron temperature, the foremost penetration depth dependence. In four ELMy H-mode Deuterium discharges 30 Deuterium pellets were injected at three magnetic field values (B_t = 1.8, 2.5, 3 T) with increasing NBI heating (P_{NBI} = 2.5, 5, 7.5, 10 MW), thereby varying electron temperature (T_{ped} = 0.26-0.79 keV) as well. The pellets were chosen to be fast, large pellets, that is v_p =600 m/s with nominal radius of 1.9 mm (nominal pellet particle content of $3.8\cdot10^{20}$ particles). The discharges have been tailored to be as similar as possible in feedforward mode, thus 2 of the 5 independent variables of the empirical scaling were kept nearly constant (κ, v_p). In case of the pellet mass, the guiding tube in the experimental setup causes a pellet mass reduction of 15(±7)%, but the variation was not enough to be able to scale the pellet mass dependence in this limited set of pellet events. For the remaining two dependent variables, the corresponding bilinear scaling obtained by ordinary least mean squares regression is shown in Table 2.

	Te	Bt
Statistical scaling	-0.67 (±0.04)	-0.41 (±0.08)
Dedicated scan	-0.57 (±0.08)	-0.63 (±0.02)

Table 2. Magnetic field dependence and electron temperature dependence of the penetration depth from the dedicated single parameter scan experiments: $\lambda \sim \overline{T}_e^{\alpha_4} \cdot B_t^{\alpha_5}$. The errors denote ±1 standard deviations.

The comparison of the statistical and dedicated discharges shows a reasonable agreement for the electron temperature. The direction of the magnetic field dependences agree, although there exists some difference between the experimental exponents, which is statistically borderline significant at a nominal 95% level. To illustrate the effect of the magnetic field, reduced residuals are used in Figure 1 to eliminate the influence of m_p and T_e by normalizing the penetration depth to these dominant dependences as shown in the figure.

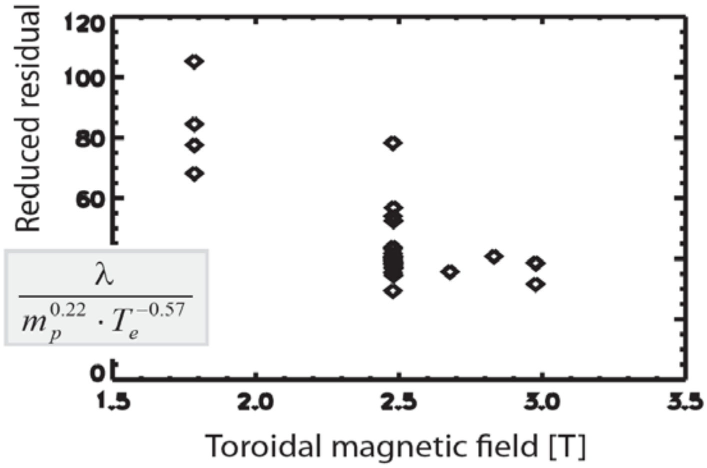

Figure 1. Magnetic field dependence from the dedicated single parameter scan experiments.

Theoretical investigations of the role of the magnetic field have then been carried out with the Hybrid ablation code [4]. The work was performed in two steps. In the first case, bilinear scans have been conducted on the electron temperature (T_{ped} = 0.26-0.79 keV based on the standard T_e and n_e profile shapes from combined, standard diagnostics of #20043) and magnetic field (B_t = 1.8-3 T) parameter regime of the dedicated experiments using the simulation code for 600 m/s large pellets ($3.8 \cdot 10^{20}$ nominal particles). The dedicated runs shown in Figure 2 show a slight positive dependence on the magnetic field that is in disagreement - even regarding its sign - to the negative magnetic field dependence of the empirical results shown earlier.

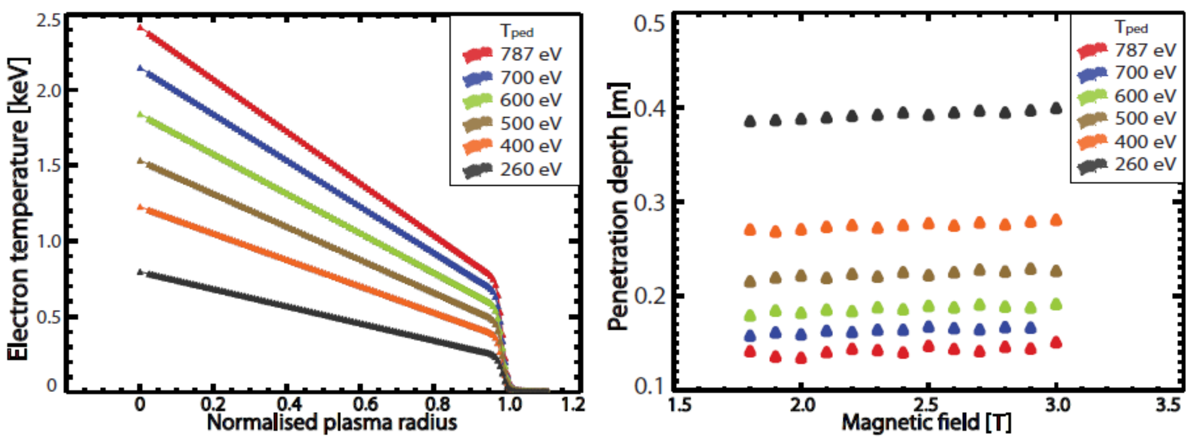

Figure 2. Penetration depths derived by the Hybrid pellet ablation code for the magnetic field range of AUG for different electron temperature profiles.

The second step focused on the simulation of the dedicated single parameter scan pellets. Four cases with three different magnetic field values have been highlighted in Figure

3 which shows the experimental electron temperature profiles and the simulated pellet ablation profiles, whereas Table 3 the corresponding simulated and measured penetration depth values. To decouple the magnetic field and the electron temperature effect, two pairs have been selected where one is kept approximately the same, whereas the other parameter is changed, showing that whereas the increase of Te (b->c) results in a distinguishable decrease of the penetration depth, the increase of Bt (c->d) however is not captured by the Hybrid code.

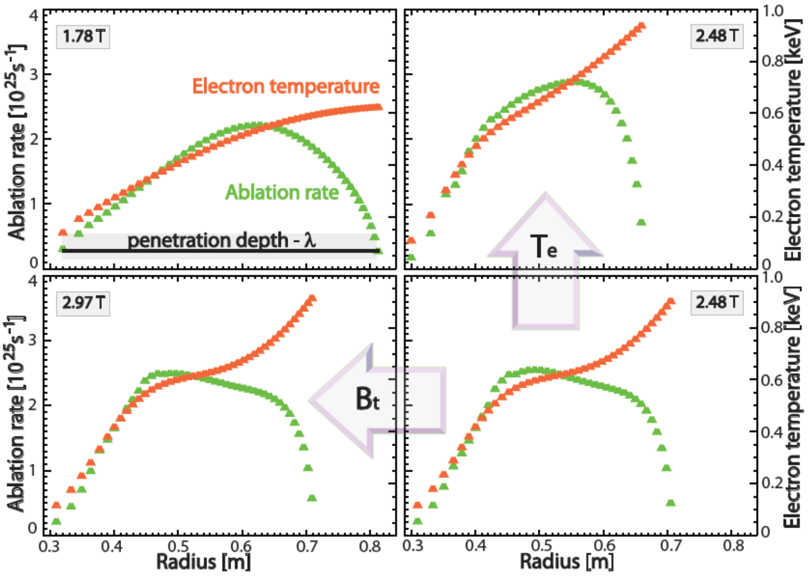

Figure 3. Electron temperature profiles and corresponding Hybrid ablation code simulations for the dedicated magnetic field scan.

Table 3. The simulated and measured penetration depth values for the dedicated magnetic field scan.

No.	B_t	λ Hybrid	λ measured
a)	1.78	0.492	0.538
b)	2.48	0.359	0.399
c)	*2.48*	*0.395*	*0.402*
d)	*2.97*	*0.399*	*0.364*

Conclusion. The empirical penetration depth scaling derived through statistical analysis of the HFS-PAD database indicated a magnetic field dependence of -0.41 (±0.08), a regression parameter not yet included in present theoretical scalings. Dedicated single parameters scan experiments conducted at ASDEX Upgrade support the relevant role of the magnetic field in pellet penetration with an exponent of -0.63 (±0.08), thus matching the importance and direction of dependence, however without reproducing the exponent quantitatively. At present there is no full theoretical understanding of this phenomena and the Hybrid ablation code also cannot describe the empirical findings showing slight positive dependences. Resulting in possibly significant overestimation of the penetration depth, this discrepancy is worthwhile to be investigated further, especially in the view of higher magnetic fields of future tokamaks such as ITER and perhaps DEMO.

References

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