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High Field Side Penetration Depth Scaling Studies at ASDEX Upgrade

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In modern tokamak experiments refueling of plasmas by the injection of frozen hydrogen isotope pellets is a promising approach. By injecting the pellets from the magnetic high field side (HFS) a grad B induced drift [1] accelerates the deposited material toward the center of the plasma, hence achieving a higher fuelling efficiency. Therefore the pellet injection system was adapted to HFS in several tokamaks, and this scenario is foreseen to be the main ITER fuelling scheme as well.

In order to further improve our understanding of the pellet ablation physics and to facilitate future scaling studies for the next generation of tokamaks, an HFS pellet injection database had been developed based on experimental results obtained at the ASDEX Upgrade tokamak. The database contains the most relevant pellet and plasma parameters determining the pellet ablation, with the aim to complete the already existing international Low Field Side (LFS) database, called the IPADBASE [2].

In this contribution a statistical analysis is presented based on the database. Model selection techniques were implemented to determine the statistically relevant parameters concerning the pellet ablation [3], and hence derive an experimental HFS scaling law for the pellet penetration depth using multiple regression analysis. In spite of earlier considerations, the electron density was found to be statistically irrelevant. The HFS Scaling Law of pellet ablation considered here has the following form:

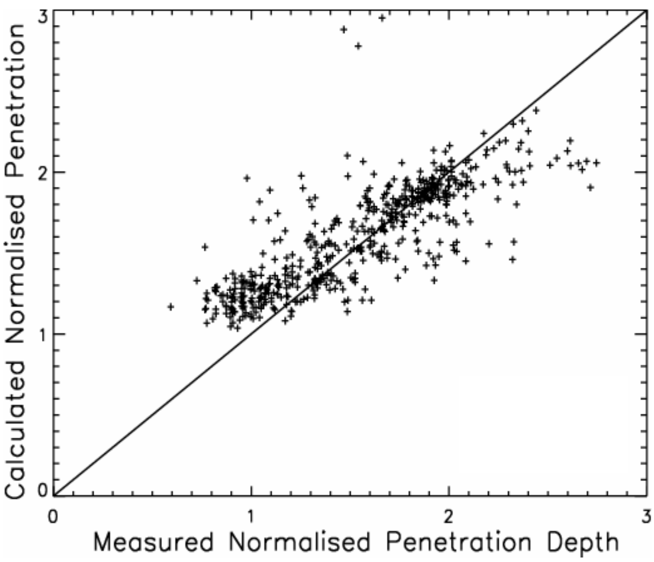
$$\frac{\lambda}{d^{0.25}} = C \cdot m_p^a \cdot v_p^b \cdot T_e^c \cdot B_t^d \cdot \left(1 + \delta_{lower}\right)^e$$

where the penetration depth (λ) is normalized to the distance between the flux surfaces 1.0 and 0.9 along the pellet path (d), as this is the range, where the pellet normally ablates. Furthermore m_p stands for pellet mass, v_p for the pellet velocity [4], T_e for the average electron temperature, B_t for the toroidal magnetic field, and δ_{lower} for the lower triangularity, that (together with the elongation and the aspect ratio) characterizes the plasma shape. In the absence of electron temperature profiles, an average electron temperature was calculated from the MHD plasma energy as follows: $T_e = W_{MHD} / \left(2 \cdot n_e \cdot V_p\right)$, where n_e is the line averaged electron density, and V_p the plasma volume. The penetration depth was calculated from the pellet's lifetime in the plasma obtained from the D_α emission measurement of the pellet cloud.

The results of the multiple regression analysis assuming an absolute measurement error of ±2.5 cm for the penetration depth are collected in Table 1, where beside the exponents and their standard deviation (SD), the statistical importance (D_{stat}) of the variable is also given. The D_{stat} quantity, motivated in [5], is the product of the variation of the parameter and the absolute value of its regression coefficient.

	m_p	v_p	T_e	B_t	$1+\delta_{lower}$
Exponent	0.226	0.207	-0.553	-0.601	-0.82
SD	0.018	0.026	0.04	0.085	0.305
D_{stat}	0.682	0.296	0.931	0.257	0.184

Table 1. HFS Scaling results



The results show a strong dependence on the electron temperature and the pellet mass. The other parameters have significant exponents in the regression as well. Figure 1. shows the relation between the measured and the calculated penetration depth from the scaling. The fit shows a marked deviation.

Figure 1. The relation between the HFS Scaling and the experimental values

The effect of the inaccuracy of the different parameters was numerically tested by stability analysis. A scan was performed by scattering the different regression variables by a given relative error. It was found that inducing a scatter of 15% for the electron temperature values, and a scatter of 40% for the pellet mass would yield a result still within one standard deviation of the corresponding exponent of the scaling. The assumption that the inaccuracy of these parameters lies within these values is realistic. The measurement error of the other parameters is negligible.

The HFS Scaling results were compared to that of the existing LFS scaling based on the IPADBASE, where the scaling study was performed on the whole database, as well as on each individual fusion device [2]. The parameters were included based on theoretical considerations. The LFS Scaling had the following form:

$$\frac{\lambda}{a} = C \cdot m_p^a \cdot v_p^b \cdot T_{e,0}^c \cdot n_{e,0}^d$$

where the penetration depth is normalized here to the plasma minor radius (a), and $n_{e,0}$ represents the central electron density and $T_{e,0}$ the central electron temperature. The LFS results based on only ASDEX Upgrade data, and as well as the HFS regression results obtained from implementing the LFS scaling form are collected in Table 2.

		m_p	v_p	$T_{e,0}$	$n_{e,0}$
LFS	Exponent	0.06	0.18	-0.41	0.07
	Sigma	-	-	-	-
	D_{stat}	0.056	0.290	1.082	0.168
		m_p	v_p	T_e	n_e
HFS	Exponent	0.305	0.249	-0.599	0.272
	Sigma	0.018	0.026	0.042	0.037
	D_{stat}	0.918	0.355	1.011	0.444

Table 2. Comparison of the LFS and the HFS Scaling Law

Both scaling shows the importance of the electron temperature with its strong exponent and high statistical importance. The exponents for the electron temperature and pellet velocity are about the same. A difference is found in the exponents of the pellet mass and the electron density. This is due to the distribution of these parameters in the two databases respectively. There is no significant variation of the pellet size present in the LFS database, therefore the regression analysis cannot show the penetration depth dependence on this variable. The exponent in the electron density in the HFS scaling is probably due to the correlation of this parameter with the electron temperature in the database.

Finally the HFS Scaling Law results are compared to the predictions of the *Neutral Gas Shielding Model* (NGS) of pellet ablation [6]. The following penetration depth scaling is obtained from this model, see [7]:

$$\lambda \propto \left(\frac{v_p \cdot m_p^{5/9}}{n_{e,0}^{1/3} \cdot T_{e,0}^{5/3}} \right)^{1/3}$$

The comparison (Table 3.) shows a good agreement for the experimental and the theoretical values in the exponent of the electron temperature. The model also describes the power of the pellet mass and velocity rather well. However in the case of the pellet velocity the difference is probably due to the fact that the NGS model does not consider the shielding effect of the ionized part of the cloud formed around the pellet. This effect is more pronounced at low velocities, as the shielding effect of the ionized cloud is higher in that case. In the HFS regression analysis the electron density was not used, i.e. its regression coefficient was set to zero.

	m_p	v_p	T_e	n_e
NGS Model Exponents	0.18	0.333	-0.555	-0.11
HFS Scaling Exponents	0.226	0.207	-0.553	-

Table 3. Comparison of the experimental HFS Scaling and the theoretical NGS model

Summary

A High Field Side pellet injection database has been developed at the ASDEX Upgrade tokamak containing the relevant experimental parameters of pellet-plasma interaction. Based on the database an experimental HFS Scaling has been derived using statistical methods. The results are compared to that of the already existing LFS Scaling and to the predictions of the NGS model of pellet ablation.

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