Observed regularity in the dissolution of solid hydrogen in plasmas

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Introduction

The large amount of experiments in which the phenomenon of the dissolution of solid hydrogen particles in plasmas is exploited for plasma recharging has been carried out worldwide since 1975 [1]. Experiments aimed at studying the interaction of solid polystyrene particles with the dense plasma of pinch discharges as radiation source have also been published in the same year [2]. Experiments using liquid drops as projectiles to act as plasma probes were started even earlier [3]. More recently, lithium [4] and carbon [5] macro-particles have also been injected in torus-shaped discharges as possible tools for plasma diagnostics.

The first theoretical study on solid hydrogen particles as secondary sources of plasma was done in 1954 by Lewi Tonks [6], in complete absence of experimental support, to assess the feasibility of recharging the plasmas trapped in the eight-shaped stellarator.

All experiments have ever since shown, as Tonks predicted, that a luminous atmosphere around a dissolving macro-particle is indeed produced, but not “at once” as he imagined. All measurements to date in fact show that the expansion time of the fluid atmosphere is not as short as required to reduce the plasma energy flux consistently with the observed small dissolution rate of the solid. Since the size of the atmosphere is observed to be of the order of centimeters, and the speed of atoms leaving the surface of the order of tens of km/s then it would need a time of order of **micro-seconds** to expand. However, if we let the penetration of plasma electrons in the solid to be of the order of their mean free path, then the dissolving time of the solid should be at most of the order of **nano-seconds.** Therefore the plasma energy flux “must” have become sufficiently small long before the expanded atmosphere could be able to reduce it by absorption. The atmosphere therefore cannot be opaque but transparent to the direct electron flux, though be still opaque for the returning flux that, by slowing down, acquires a considerable cross section for inelastic collisions and makes the atmosphere “visible”. The aim of the present paper, however, is not to predict the correct reduced energy flux or the dissolution rate, but simply to point out that it is possible to determine the electric field at the solid-fluid boundary of dissolving projectiles in plasmas by using the empirical dissolution average rate (or the penetration length). Such **conjecture** allows us to find out, in some randomly chosen experiments, that the electric field is **regularly** of the order of, and in most cases less, than the external magnetic field, as pointed out long ago [7].

Penetration and Deflection of projectiles in plasma

Anestos and Hendricks in 1974 [3], who first injected alcohol drops into a linear discharge, observed and measured the deviation of the negative charged drops and used it to **probe** the electron temperature of the magnetized linear plasma. Jorgensen et al., [1], who first injected solid hydrogen macro-particles into the linear Puffatron device, and Foster et al. [8], who first injected them into the torus-shaped Ormak device, measured both the dissolution rate of solid hydrogen and the displacement of the solid projectile from its inertial trajectory. Such deviations can be shown to be the effect of the interaction of the negative charge collected by the projectile with the external electric field in the first case, and of the interaction of the magnetic moment with the gradient of the external magnetic field in the second case [9] [10]. The measurement of the deviation allows the direct calculation of the quantity of charge collected at the solid-fluid boundary and therefore the electric field **E*.** If we invoke the electric charge continuity at the plasma-solid boundary, the charging time would be given by $\mathbf{t}^* = 4\varepsilon\mathbf{E}^* / e n_e \bar{C}_e$ [10], where ε is the dielectric constant, e the electron charge, n_e and $\bar{C}_e$ are the density and random speed of the target plasma electrons respectively. Experiments [1] and [8] indicate that **t*** is of the same order of magnitude of the dissolution time $\tau^* \equiv 1/\left(n_0 \sigma U\right)$, which is the dissolution time of a solid layer as thick as the mean free path of the plasma electrons in the solid $\lambda^* \equiv 1/\left(n_0\sigma\right)$, where σ is Lenard's cross-section for the diffusion of electrons in hydrogen, U is the average empirical dissolution speed and n_0 is the number density of the solid. This observation suggests that the dissolution and the charging processes may be closely related.

Observed Regularity during dissolution of solid hydrogen projectiles in plasmas

If, in the definition of the dissolution speed $U \equiv \boldsymbol{\lambda}^*/\boldsymbol{\tau}^*$ of the solid layer, we replace the dissolution time $\boldsymbol{\tau}^*$ with the charging time $\boldsymbol{t}^*$, which can be obtained directly from the measurement of the deviation from the inertial trajectory, U can be also calculated and compared with the average empirical speed, which can be obtained directly from the injection speed and penetration measurements, whenever the electric field is also known. Therefore, for those experiments in which deviation and penetration have been measured [1] [8], both the electric fields and the dissolution speed can be calculated and compared with experiments. In those experiments [11]-[18] in which measurements of deviation are not available, the electric fields can still be calculated as a function of the dissolution speed and, as it has bee found for experiments [1] and [8], found to be of the order or less than the external magnetic field, as it has bee suggested long ago. In fact if we adopt the conjecture which identifies $\boldsymbol{\tau}^*$ with $\boldsymbol{t}^*$ and solve the equation $\tau^* = \boldsymbol{t}^*$ for the electric field E* and divide both sides of the expression by the external magnetic field B in Gauss, we may rearrange the right side of the equation as a ratio of two dimensionless quantities $\alpha = \alpha(T_e,\mathrm{B})$ and $\beta = \beta(n_e,T_e)$:

$$\alpha^* = \frac{\mathbf{E}^*}{B} = \frac{e/(4\varepsilon\sigma B)}{n_0 U / n_e \bar{C}_e} \equiv \frac{\alpha}{\beta}$$

where σ is in cm^2 and can be easily calculated using the instructions by Brode [19], U is in cm/s, and n_0 in cm^{-3}; n_e and $\bar{C}_e$ are the density and random speed of the target plasma electrons respectively, in the same units. However, if we recall that $\varepsilon = 1.2$, $e = 4.8 \times 10^{-10}$ e.s.u., $n_0 = 6 \times 10^{22}$ cm^{-3}, 1 Tesla = 10^4 Gauss and 1 Å^2 = 10^{-16} cm^2, we get $\alpha = 100/(\hat{\sigma} B_T)$, $\beta = 600 \underline{U}/n_{13}\bar{C}_9$, where $\hat{\sigma}$ is in Å^2, and B_T in Tesla; $\underline{U}$ is in m/s, n_{13} in units of 10^{13} cm^{-3} and $\bar{C}_9$ in units of 10^9 cm/s. From some randomly chosen experiments among the many available nowadays, it can be noticed that the ratio $\boldsymbol{\alpha}^* = \alpha/\beta$ is in most cases of the order of unity, as well as a large fraction of 1 as shown in the table below.

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Table

Experiment	$\bar{R}_{eq}$, μm	τ, μs	$\underline{U}$ m/s	n_{13}	T_e, keV	$\bar{C}_9$	$\hat{\sigma}$	B_T	β	α	α*
1975 Puffatron(*)	142 ($\Delta\bar{R}_{eq}=29$)	100	0.29	≤ 40	0.025	0.32	4.4	1.5	600/n_{13}	15	≤ 1
1975 Ormak	35	422	0,083	0.7	0.056	0.47	2.6	1.8	151	22	0.14
	105	880	0.12	1	0,135	0,73	1.57	1.1	98	58	0.59
1977 Pulsator	262	450	0.58	3	0.01	0.21	5.8	< 2.7	130	17.2/B_T	0.13/B_T
1978 ISX-A	363	360	1,01	2.5	0.43	1.3	0,80	1.32	186	95	0.51
1979 ISX-B 10150	570	250	2.28	4	0.69	1.65	0.52	1.1	207	175	0.84
10030	570	300	1.90	1.5	1.1	2.08	0.38	1.1	365	239	0.65
10347	570	444	1.28	1.5	0.5	1.4	0.72	1.13	367	123	0.34
1989 JT-60	1800	500	3.60	6	3	3.45	0.28	4.5	104	79	0.76
1989 TFR H	408	171	2.4	1.2	2	2.81	0.28	2.2	425	162	0.38
D	408	218	1.9	1.2	2	2.81	0.28	2.2	333	162	0.49
1992 JET 20387	2280	669	3.41	4	3	3.45	0.28	2.8?	148	128	0.86
20732	1539	970	1.59	2.3	2.36	3.06	0.28	2.8?	135	128	0.94
1992 Alcator-C 930817007	500	87	5.75	10	1	2.81	0.4	5	123	50	0.41
930817015	660	150	4.40	10	1	2.81	0.4	5	94	50	0.53
2004 FTU 18598	746	188	3.97	20	1.5	2.43	0.3	8	49	42	0.85
12744	746	188	3.97	20	1.5	2.43	0.3	7	49	48	0.97
China HL-1M	600	320	1.88	4	0.8	1.78	0.47	2.4	158	89	0.56

(*) In this experiment, the pellet is only partially dissolved during the 100 μs interaction time