Dust capture experiment in HT-7

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Abstract. A dust capture experiment was conducted in HT-7, a medium-sized superconducting tokamak of the Chinese Academy of Sciences. An aerogel was used to intercept fast particles propagating along the ion flow. The particles produced sizable impact craters, which were characterized and measured using 3D computer tomography and a seed growing algorithm. Captured particles were also photographed and measured. This allowed the determination of average impact yields, which were approximately more than four times the particle (projectile) mass. We provide evidence that the particle velocities may reach the hypervelocity regime, i.e. $v_p \geq O(1 \text{ km s}^{-1})$.

Contents

1. Introduction 2
2. Dust capture experiments—preliminary considerations 3
3. The experiment 3
4. Results 6
5. Discussion 11
6. Conclusion 12
References 13

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1. Introduction

Clean energy production in plasma fusion reactors is a vision that is both fascinating and to some extent elusive. Many years of painstaking research and development have been devoted to this goal, and it appears that with the International Thermonuclear Experimental Reactor (ITER), a first working experimental reactor will become available in the not too distant future. Not all design problems have yet been solved, however. One of these is the production of dust particles in the reactor itself. Plasma–wall interactions cannot be avoided, only alleviated, and dust production is a major concern. According to the 2006 Mitsubishi Report, ITER may be expected to produce 750 kg Be and 150 kg C dust particles during one year of operation, whereby in a recent paper by Rosanvallon et al [1], the safety limits for dust inventory have been set to 100 kg W, 100 kg Be and 200 kg C. The concerns are core plasma contamination, re-deposition on the walls, roughening the surfaces and blocking gaps in tiles left for engineering purposes, trapping of radioactive tritium in the dust, the possibility of H-explosion due to Be-dust in the divertor and, of course, the refurbishment problem [2]–[4].

To resolve this issue and to advance towards the goal of dust-free reactors (ideally), one needs to understand the dust production well enough to simulate the process for reactor design purposes. Summarizing the available information from measurements taken in different tokamaks yields the following picture:

1. The dust size distribution peaks around 1–10 µm and falls off smoothly to beyond 100 µm.
2. The propagation direction of the small dust particles follows (mostly) the scrape-off layer (SOL) plasma flow.
3. Observed particle velocities are 10 s of m s\(^{-1}\) up to about 0.5 km s\(^{-1}\).
4. Particle lifetimes in the SOL are estimated to be up to \(\sim 100\) ms.

See e.g. [5]–[9]. However, there are some unresolved issues. There is evidence [10, 11] that the velocity spectrum of dust in tokamaks may reach significantly beyond 1 km s\(^{-1}\) (the so-called high-velocity-HiV particles). Also, the scaling of existing tokamak data to other reactors, in particular ITER, including all the relevant physical processes of charging, sputtering, thermodynamics, radiation, transport, etc is not yet advanced enough, although significant progress has been made recently (see [12, 13] and references therein).

The particle velocity issue is of particular relevance, because impacts at speeds \(v \geq 1\) km s\(^{-1}\) generate more ejecta mass than that of the original projectile. In principle, this could lead to runaway erosion in larger tokamaks operating continuously for longer periods. Since it takes time to accelerate dust particles to such high velocities, attention is naturally focused on the SOL, since here particle lifetimes against erosion are longest. For recent numerical modeling of HiV particle distributions (see [9, 14]).

In order to obtain direct information about dust particles in the SOL of the tokamaks, capture experiments using aerogels would appear to be particularly useful, especially for hypervelocity impacts. Laboratory experiments have shown [15] that such particles leave long tracks and are captured virtually intact. This allows is the determination of the particle mass, velocity and direction, i.e. \(f (m, \vec{v})\) and in principle also the positional dependence inside the reactor as well as the temporal evolution.
2. Dust capture experiments—preliminary considerations

Silica (SiO$_2$) aerogel is used for capture experiments. This consists of nanometer-sized spheres with up to 95% empty space, i.e. densities of the order 0.1–0.3 g cm$^{-3}$. Exposure to deuterium ions with a flux $5 \times 10^{19}$ cm$^{-2}$ s$^{-1}$, density $10^{13}$ cm$^{-3}$, temperature 30 eV, yields a sputter erosion rate of $3 \mu$m s$^{-1}$, i.e. a contamination of the plasma of $3 \times 10^{-5}$ g cm$^{-2}$ s. Since the yield function decreases sharply with particle energy, a temperature of 10 eV would result in a factor of 10 smaller contamination (see section 3.2 in [3]). To avoid plasma contaminations the dust capture experiments are restricted to ten 1 s shots. From impact experiments on aerogels [16], the track length as a function of particle diameter and velocity has been determined. For projectile velocities of 5–6 km s$^{-1}$ (which we used as our upper design limit), track lengths of 1 cm (aerogel density of 0.1 g cm$^{-3}$) and 0.4 cm (aerogel density of 0.18 g cm$^{-3}$) were found. To ensure absorption of all particles in the target, we used an aerogel of 25 mm thickness. From scaling of previous measurements with HT-7 [17], we obtained a preliminary expected dust particle flux of $8 \text{ particles cm}^{-2} \text{ s}^{-1}$ after 8 s of operation. For an aerogel area of 6 cm$^2$ and 10 s of operation this leads to an expected total number of impacts (assuming a uniform spatial distribution in the SOL) of about 100 impacts. At 5–6 km s$^{-1}$, the entrance hole was three times the projectile size (aerogel density of 0.1 g cm$^{-3}$) and twice the projectile size (aerogel density 0.18 g cm$^{-3}$). For the higher density aerogel, the ‘source confusion’ due to overlapping impact entrance holes (assuming 100 projectiles) is 2%, for the lower density 5%. To be on the safe side, this gave the preference to the higher density aerogel.

3. The experiment

HT-7 is a medium-sized superconducting tokamak and normally operated with $I_p = 100 \sim 200$ kA, $B_t = 2$ T, major radius $R = 1.22$ m, minor radius $a = 27$ cm, line-averaged density $n_e = (1 - 5) \times 10^{19}$ m$^{-3}$, $T_e = 0.3$–2 keV, with limiter configuration. The lower hybrid current drive (LHCD) system consisted of a multijunction grill (4 x 12), a 1.2 MW wave system with a frequency of 2.45 GHz. Efforts have been made for steady state operation and many good results have been obtained during the past few years. The longest plasma duration was over 300 s by LHCD with a central electron temperature of 1 keV [18, 19].

The plasma is limited with two toroidal limiters and one belt limiter, as shown in figure 1 [20]. The total plasma facing surface area of the HT-7 graphite limiters is about 1.88 m$^2$. All plasma facing materials for limiters are made from the GBST1308 (1% B, 2.5% Si, 7.5% Ti)-doped graphite with about 100 $\mu$m SiC coating [21]. The rest of the plasma-facing surface is formed by the stainless steel liner within a metallic torus with $r = 33$ cm. The effective plasma-facing area of limiters and liner is about 12 m$^2$. In HT-7, after plasma operation, abundant dust particles have been observed. Post-analysis showed that the dust in HT-7 mainly consists of C, Si and B. Other elements, such as Fe, Cr, were rare. During plasma discharges, dust particles were also observed by an electrostatic dust detector in situ and in real time. The data were in good agreement with bursts that appeared on multichannel H radiation and on multichannel electron cyclotron emission (ECE) diagnostics [17].

The aerogel sample designed for dust capture in HT-7 was inserted in a stainless steel box, as shown in figure 2. The aerogel sample was 36 mm in length, 26 mm in width and 25 mm in depth. The box was open and allowed dust injection from the ion flow direction. During plasma discharges, the box was inserted in the SOL. The box was introduced over the liners in...
Figure 1. Plasma vessel of HT-7 superconducting tokamak. (TL: toroidal limiter; PL: poloidal limiter; BL: belt limiter, ICRF: ion cyclotron resonant frequency system.)

Figure 2. Set-up of aerogel sample for dust capture in HT-7.

HT-7 and the top of the box was 20 mm away from the main plasma. Thus, the aerogel sample could catch dust particles from a radius of 292–328 mm traveling in the poloidal direction (see figure 3).

The experiment was performed under the following conditions: plasma current \( I = 130 \text{ kA} \), plasma density \( n_e = 1.5 \times 10^{19} \text{ m}^{-3} \), toroidal field \( B = 1.8 \text{ T} \), LHCD power \( P = 300–420 \text{ kW} \), pulse duration is about 1 s. The graphite limiters were actively water-cooled and the wall temperature was about 30°C. Altogether ten plasma discharges were operated for dust capture. figure 4 shows the aerogel before and after plasma exposure.
Figure 3. Set-up of the superconducting tokamak HT-7, including the positioning of the aerogel probe.

Figure 4. Aerogel probe before and after plasma exposure. The metal stripe holding the aerogel is already cut open for aerogel removal in the right-hand side picture.
Figure 5. Two consecutive slices of the aerogel probe as visualized using μCT imaging.

4. Results

The aerogel sample provided to us by the manufacturers was denser than stated in the description (a ‘dense aerogel’ with 0.25 g cm$^{-3}$ instead of 0.18 g cm$^{-3}$). This makes a large difference regarding the impact physics. From the measurements of Burchell et al [15, 16] it was concluded that at around 0.2 g cm$^{-3}$ there is a transition in the physics from an impact into a ‘dissipative (porous) medium’, which in the limit tends to the classical ‘momentum solution’, to an impact into an ‘energy dissipative medium’, where the excavated mass is proportional to the projectile energy. For our measurements, this has two important consequences:

1. The impacts were not narrow tubes (as one would expect if the momentum solution applied). Rather they resembled classical craters as in all the other energy dissipative systems studied. However, for our parameters (density ratio, target yield strength, etc) no measurements exist with which we could calibrate our results.

2. The impacting dust particles were captured by the aerogel, but only so loosely that they fell out of their impact sites. We thus have impact crater measurements and particle measurements, but do not know their correspondence. Also, some of the particles were lost during extraction of the aerogel from the tokamak site.

The data acquisition and analysis involved three steps:

1. Three-dimensional (3D) μCT imaging of the aerogel probe was performed at the Scanco Laboratory in Bruetisellen (Switzerland) (www.scanco.ch). Two consecutive slices of the 3D image data, which were acquired with an isotropic spatial resolution of 5 μm, are displayed in figure 5.

2. Based on these 3D μCT images and the fact that the inner surface of the craters were compacted, a segmentation procedure was applied. This involved some smoothing, binarization (i.e. division into aerogel and air), setting a ‘seed point’ in the crater of interest and using a seed growing algorithm to identify the whole crater volume.
Figure 6. Schematic view of the distribution of the craters and their radii.

Figure 7. EDX-measurement for an aerogel sample without particles (left), for an aerogel with impact craters (middle) and for dust particles (right).

3. Manual post-processing (to account for the ‘leaking’ of the seed growing algorithm, some source confusion, overlaps, etc) finalized image acquisition and analysis procedure.

In this way, 27 craters were segmented and further analyzed. This number is in remarkably good agreement with the earlier particle flux measurements \[17\]. The results are as follows.

Figure 5 shows two consecutive cross sections of the 3D µCT image. Note that the rims and surfaces of the craters are denser (appear darker in the image) suggesting compaction and (perhaps) melting and solification. In figure 6, we show the crater distribution in the \(x\)–\(y\)-plane and their size as estimated by their radius. As expected, no regularities—be it in the spatial distribution or in the size of the craters—can be observed.

Figure 7 (left panel) shows energy dispersive x-ray (EDX) analysis measurements of the composition (mainly Si and O) of the aerogel, figure 7 (middle panel) shows the composition (mainly C, Si and O) of the inner surface of the ‘craters’ and figure 7 (right) shows the
composition of the captured particles (mainly C and O). The large abundance of C found in the crater surfaces suggests that some of the impacting particle material has ‘contaminated’ the aerogel surface inside the craters. The composition of the collected particles is consistent with earlier HT-7 post-analysis dust measurements [17], which showed mainly C, Si, B and traces of Fe, Cr, with the exception of oxygen, which was not present in the earlier analyses. We interpret the O-abundance as possibly due to contamination from the aerogel. This ‘contamination’ of the craters and of the collected particles strongly supports the conclusion (see later) that the impacts were not ‘soft’ or ‘cushioned’.

Figure 8 gives the histograms of crater radii and crater depths. Figure 9 shows the measured volume of the craters, again in histogram form. These three quantities, radius, depth and volume, are the basic impact information available. These results show, not unexpectedly, that the small craters dominate; however, they also show that the smallest craters identified are substantially larger than the 5 μm resolution. Presumably there are also craters at the resolution limit, but these were not segmented to avoid ambiguities. A closer look at the craters reveals that the surface of (nearly) all craters is coated with a thin film of very dark voxels, which indicate much denser material that the surrounding aerogel or air. To estimate the amount of densified material and its origin we performed the following analysis. For each crater, we determined the volume of the film of denser material as a function of the intensity threshold, which is the value according to which we segment densified (and therefore darker) material from normal aerogel material (see figure 5). Next, we calculated the ratio of film volume to crater volume, \( r = V_{\text{film}} / V_{\text{crater}} \).

Figure 10 shows the mean value \( \langle r \rangle \), when averaged over all craters as a function of the intensity threshold \( I_t \). If we choose the cutoff value somewhat arbitrarily \( (I_t = 50) \) but with all due caution to segment the completely compacted regions, we find that this region amounts on average to 3.4% of the crater volume. We estimate a mean density ratio for this threshold value of 3.5, which corresponds to the intensity ratio of compacted to unperturbed aerogel. On this basis, we find that approx. 12% of the crater mass has been compacted. This means on the other hand that almost 90% of the crater mass is ejected. From the EDX measurement we know, however, that the material at the crater rims also contains a certain amount of carbon. This fact
implies that the high density film at the rims of the craters also consists of ablated material of the infalling projectile. In conclusion, the observation of overdense regions at the crater rims and their subsequent analysis suggest that a certain percentage of aerogel material as well as ablated projectile material has been compacted at the crater rims. Most likely partial melting of the material led to the compaction. However, it appears that a considerable fraction of the crater mass has been ejected.

Assuming melting to be the dominant process of compaction, we perform the following countercheck, which even allows us to estimate the energy and thus the velocity range of the projectiles. For melting, a latent heat of fusion $L$ has to be provided. This melting energy $E_m$ can be considered as a lower bound for energy of the projectile $E_p \geq E_m = m_{\text{molten}} \times L$ ($m_{\text{molten}}$: mass of molten material, $L = L(\text{SiO}_2) = 188 \text{ J g}^{-1}$). Knowing the projectile mass one can infer its velocity $v_p > \sqrt{2E_m/m_p}$. Figure 11 shows the distribution of the so-determined melting energies as well as $E_m$ as a function of the crater volume.

Figure 12 shows images of some of the dust particles collected. The measured range of volumes of these impacting particles extends from $4 \times 10^{-13}$ to $2.4 \times 10^{-11} \text{ m}^3$, i.e. they are typically a factor of 50 smaller than the excavated volumes. In terms of masses—assuming 12% molten aerogel mass and a typical projectile density of 2.5 g cm$^{-3}$ (in line with earlier findings that the dust particles consist mainly of the plasma-facing limiter materials—doped graphite with 100 $\mu$m SiC coating) yields a typical ratio excavated mass/impacting mass of approx. 4.4—in other words, more mass is ejected than is impacting. We deduce this ejecta/projectile ratio by assuming that the largest particles are associated with the biggest craters. This is the most conservative assumption. Any other association must lead to an even larger ratio. Assigning once again the smallest/largest collected particles with the smallest/largest identified
Figure 10. ⟨V_{film}/V_{crater}⟩ as a function of the intensity threshold $I_t$. The error bars are the standard deviations. The dashed line signifies the selected threshold used for the calculations.

Figure 11. Left panel: distribution of the melting energy $E_m$. Right panel: $E_m$ as a function of $V_c$. The black line indicates the best fit with a scaling exponent of 1.42.

craters, we can estimate an absolute lower limit to the particle impact velocities by assuming that 100% of the kinetic energy is converted into compaction by melting (i.e. ignoring the 90% ejecta energy completely). We find particle velocities of $v_p \gg 167 \text{ m s}^{-1}$ for the smallest particle and $v_p \gg 764 \text{ m s}^{-1}$ for the largest.

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5. Discussion

For high velocity impacts (energy solution), we have the experimentally well-verified relationship [22, 23]:

\[ \frac{M_E}{M_P} = K v_p^2, \]  

(1)

where \( M_E, M_P \) are the ejecta and projectile masses, \( v_p \) is the projectile velocity and \( K \) is a constant, which depends on material properties. With \( v_p \) in km s\(^{-1}\), measured values for \( K \) are 5 for basalt projectiles and target, and 2.6 for iron projectiles and aluminum target [24, 25]. Clearly, \( K \) depends on material properties. In our case (dense aerogel) the appropriate value for \( K \) is not known; indeed the evidence that equation (1) holds is also not verified. But in any case, since the thin lining of compacted material in the crater wall only accounts for approx. 12% of the crater material, the basic result that on average the ejecta mass is at least 4.4 times the mass of the impacting particle, can be regarded as firm. We can make two independent plausibility checks to see, if the energy solution (1) holds in principle: Firstly, a simple approximation for the crater topology for normal impacts yields [26, 27]:

\[ \frac{l_c}{d_p} = 1.96 \left( \frac{\rho_p}{\rho_t} \right)^{1/2} \left( \frac{v}{c_t} \right)^{2/3}, \]  

(2)

\[ \frac{d_c}{d_p} = 3.9 \left( \frac{\rho_p}{\rho_t} \right)^{1/2} \left( \frac{v}{c_t} \right)^{2/3}, \]  

(3)

where \( l_c \) is the crater depth and \( d_c \) its diameter, at the surface. The material densities are \( \rho \), with the subscripts ‘t’ for target and ‘P’ for projectile. \( c_t \) is the sound speed in the target. The projectile diameter is \( d_p \). For the momentum solution, similar expressions as (2) and (3) are obtained [26, 27] with a velocity exponent of 1/3. According to these expressions, we get a very simple relationship \( d_c/l_c \approx 2 \), which can be checked.

In figure 13 (left panel), we show the data, together with the above prediction, as well as the best fit. The data are compatible with this simple theoretical prediction. However, the best fit departure from the expected exponent of 1 may indicate an impact regime intermediate...
Figure 13. Left panel: crater depth versus crater radius. The grey line indicates the best fit yielding an exponent of 1.4. The black line is obtained using an exponent of 1.0 as derived from theoretical considerations. This line also represents a good fit to the data, especially if the very small craters are less weighted. Right panel: square of the crater radius times the crater depth versus the measured crater volume. The best fit line and the theoretical line fall together.

to the energy and momentum solution, in particular for the small craters. Secondly, impact craters are expected to have conical shapes, so that their volume is proportional to $\pi/12(d_c^2l_c)$. In figure 13 (right panel), we compare this expression with the measured crater volumes and find good agreement (best fit exponent 0.98). While this ‘compatibility test’ suggests that the ‘energy solution’ is indeed more appropriate for our experimental data rather than the momentum solution, it does not yield information about the particle velocities, since the constant $K$ in equation (1) is not known. This is important, because a larger ejecta mass (compared with the projectile) for impacts on aerogels does not automatically imply that we have a clear signature of HIV particles since these are particles (if they exist) which would excavate more than their own mass in impacts with the walls, i.e. materials that are very different from aerogels.

6. Conclusion

It was shown that aerogel capture experiments during tokamak operation are a feasible way to obtain data about dust particles produced. Plasma erosion did not yield noticeable contamination in timescales adequate for sufficient particle impacts to be detected. Using lower density aerogels therefore should not present operational problems either. The available data from this experiment yielded average information for a limited sample of events. Twenty seven impact craters were seen and further analyzed and six particles were collected; unfortunately they did not remain buried inside ‘their’ craters. Crater shapes were conical, as is expected from high velocity impacts, and the crater diameter/depth ratio was compatible with simple theoretical predictions of the ‘energy solution’. Using a conservative estimate (largest craters correspond to the biggest particles, smallest craters to the tiniest particles found) gave an average ratio of ejecta mass/projectile mass of approx 4.4. A simple and extreme lower limit of the particle velocity
based on the molten material found at the rims of the impact craters yielded velocities of a few hundred meters per second, i.e. the hypervelocity regime can be reached. Further measurements using lower density aerogels are in preparation. These will explore the physically very different ‘momentum solution’ impacts expected for dissipative porous media.

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