DIRECT OBSERVATION OF THE DUST-TRAPPING PHENOMENON

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Abstract

Dust trapping is a phenomenon known to cause a sudden decrease in beam lifetime at electron storage rings. It has been one of the most serious operational problems at the Photon Factory Advanced Ring (PF-AR) since the 1980s, and many efforts have been made to resolve it. In a recent experimental study on dust trapping, video cameras fortuitously captured the culprit, recording a luminous micro-particle trapped in the electron beam, just as if a shooting star were traveling in the beam tube. In successive research, supersensitive cameras repeatedly observed trapped dust particles, and revealed that they behaved differently under different conditions. This article summarizes the experimental results, as well as some theories about dust trapping that are consistent with the observations.

INTRODUCTION

Stored beams in circular accelerators are susceptible to lasting interaction with particles of opposite polarity. In electron or antiproton storage rings, the beam captures positively charged ions or dust particles. The latter phenomenon is called dust trapping, and a hypothesis that explains the observations was proposed in the early 1980s [1-3].

Dust trapping often causes operational problems because it can severely disturb stored beams; it leads to a sudden decrease in the electron beam lifetime and to a sudden increase in the antiproton beam emittance. In this article, we mainly discuss the phenomenon in electron storage rings.

During dust trapping, gamma-ray bursts are often detected at the extension of the beam orbit as a result of bremsstrahlung scatterings between the electron beam and the trapped dust particle [4-6]. This can also cause operational problems to users of synchrotron radiation (SR) and high-energy physics when it occurs upstream of the beam line and detectors [7-9]. In experimental research on dust trapping, however, detection of such gamma rays has provided indirect evidence of the interaction between beam and dust.

In order to clarify the mechanism behind this phenomenon, dust-trapping theories consistent with observations have been developed, considering dynamic and thermal conditions for trapped dust particles [2, 10-16]. These theories explain how the dust can remain trapped for a long time in spite of the interaction with high-intensity stored beams. The main theories will be briefly reviewed in Chapter 2.

From an operational point of view, it is important to locate the dust sources and then to take effective measures to suppress the dust trapping. Some known dust sources will also be reviewed in Chapter 2.

At KEK PF-AR (formerly called "TRISTAN AR"), dust trapping occurred more frequently following the major reconstruction in 2001. Our long-term investigation on the phenomenon suggested that distributed ion pumps (DIPs) produced dust particles, so we installed more than 60 sputter ion pumps to replace the DIPs [17]. However, switching all the DIPs off suppressed the occurrence by only 50%, suggesting that there were other dust sources at PF-AR. Further investigation indicated that electric discharges at some in-vacuum undulators or a feedback kicker were causing dust trapping, so we surface-conditioned these discharge-prone devices by storing 25% higher beam current than usual. As a result, the occurrence of dust trapping was suppressed by 70% compared to that before taking the countermeasures [18].

In addition, we started an experimental study at PF-AR which was primarily designed to intentionally replicate dust trapping by simulating the above two conditions for dust production. In one experiment, we fortuitously observed a trapped dust particle with video cameras [19], and found it effective to conduct the dust-trapping research by direct observation [20]. Important results of the experimental demonstrations and the dust-trapping observations will be presented with some video snapshots in Chapter 3.

DUST-TRAPPING PHENOMENON IN STORAGE RINGS

Previous Reports on Dust Trapping

In the early 1980s, the dust-trapping phenomenon started to be reported around the world. The CERN Antiproton Accumulator (AA) suffered from unexpected sudden increases in beam emittance, and the phenomenon was so mysterious that they nicknamed it "AA-ghost" [3]. They concluded later that the phenomenon was related to dust particles stirred up by vibration of stochastic cooling shutters [21].

Also in the 1980s, some second-generation light sources such as PF-ring [22, 23] and NSLS [2] experienced the problem that the beam lifetime suddenly dropped and the stored beam decayed faster. At PF-ring, they found that the phenomenon occurred less frequently when the DIPs were switched off [22].

Until around 2000, dust problems were often reported at electron storage rings for light sources and for high-energy physics such as TRISTAN AR [5], DCI and SuperACO [6], CESR [13], HERA, DORIS and PETRA [24-26], ESRF [27], KEKB [9], PEP-II [8], and BEPC [28].

Experimental studies on dust trapping have been carried out at several accelerators. In the early 1990s, Marin observed bremsstrahlung bursts at SuperACO and DCI [6], and revealed that trapped dust moved

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longitudinally along the beam orbit [11]. They reported that, in contrast to the electron beam mode, the beam currents decayed smoothly when positron beams were stored [6, 29]. The same results with positron beams were also obtained at PF-ring [30], TRISTAN AR [31], HERA and DORIS [24], KEKB [9], PEP-II [8], and BEPC [28], which strongly supported the dust-trapping hypothesis.

Around the same time, Saeki et al. conducted similar experiments at TRISTAN AR, and detected bremsstrahlung bursts as evidence of dust trapping [5]. Furthermore, they tried to experimentally replicate the phenomenon by introducing dust particles on the bottom of a vacuum chamber [12], but the phenomenon was not well reproduced. Kato and his team carried on the study with a different approach: they dropped dust particles from the top of a vacuum chamber, and showed that the dust trapping could be replicated by dropping micron- or sub-micron-sized particles of high melting point such as diamond and TiO_2 [32]. Kanazawa summarized statistics from one year of AR's operation in 1993; the dust size estimated from the reduction in lifetime during the dust trapping was mostly in the range of 0.5–2 μm in diameter (assuming them to be alumina spheres) [31].

Also in the 1990s, Kelly et al. carried out statistical studies at HERA and DORIS. They investigated the behavior of dust particles by analyzing loss monitor signals [7, 33]. Moreover, they proposed a multi-particle trapping model to explain the observed beam lifetimes [34].

In 2000, the BaBar detector at PEP-II suffered frequent background noise attributed to bremsstrahlung from dust particles trapped in the HER electron beams. Wienands' team verified this phenomenon by intentionally provoking dust trapping using a remotely powered solenoid ("thumper") attached to a vacuum chamber [8].

But in fact, problems related to dust particles had occurred earlier. In the early 1960s, the first electron-positron collider AdA suffered a sudden loss of the stored beam, which was found to be caused by dust particles [35, 36].

Dust problems were also reported at proton machines. In 1971, the first hadron collider ISR in CERN was afflicted with unexpected increases in the beam loss rate. They tried to stir up dust particles by using a shaking device [37], and suspected that the problem was caused by the ceramic "wool" used for thermal insulation in vacuum [38]. Since 2010, the CERN LHC has suffered from abrupt increases in the beam loss rate and occasional beam dumps. Systematic investigation has revealed that these events were caused by micron-sized dust particles, which they call UFOs, and injection kicker magnets were identified as one of the major sources of the dust [39-41].

Dust-trapping Theories

Dynamic Stability

Calculation of one-dimensional dynamics considering the stability conditions of a trapped dust particle gives a critical mass-to-charge ratio. Here, we only consider the dust motions in the vertical direction to avoid complex horizontal motions in dipole magnets. The vertical position of a dust particle y and its velocity $\dot{y}$ can change with the passage of an electron bunch as follows [42]

$$\begin{pmatrix} y \\ \dot{y} \end{pmatrix}_1 = \begin{pmatrix} 1 & 0 \\ -a & 1 \end{pmatrix} \begin{pmatrix} y \\ \dot{y} \end{pmatrix}_0 \quad (1)$$

where a denotes the kick parameter, i.e., the attraction received during the passage of the bunch, and is given by

$$a = \frac{N_e}{n_b} \frac{2 r_p c}{\sigma_y \left(\sigma_x + \sigma_y \right)} \frac{Q}{A} \quad (2)$$

where N_e is the total number of electrons in the beam, n_b is the number of bunches, r_p is the classical proton radius, c is the speed of light, σ_x and σ_y are the rms beam sizes in the horizontal and vertical directions respectively, Q is the charge number of the dust, and A is the dust mass in the unified atomic mass unit (i.e., the total number of nucleons in a dust particle).

After the bunch passage, the dust particle drifts during the bunch spacing time τ_b, and its motion is given by

$$\begin{pmatrix} y \\ \dot{y} \end{pmatrix}_2 = \begin{pmatrix} 1 & \tau_b \\ 0 & 1 \end{pmatrix} \begin{pmatrix} y \\ \dot{y} \end{pmatrix}_1 \quad (3)$$

Finding a condition under which the movement does not diverge even while the bunch passage periodically repeats, we derive the mass-to-charge ratio A/Q, which should satisfy the condition:

$$\frac{A}{Q} \geq \left(\frac{A}{Q} \right)_c = \frac{N_e}{n_b} \frac{r_p c \tau_b}{2\sigma_y \left(\sigma_x + \sigma_y \right)} \quad (4)$$

where $(A/Q)_c$ is the critical mass-to-charge ratio.

Dust particles that satisfy the above condition can be stably trapped while oscillating transversely around the beam orbit. For example, a titanium sphere of 1-μm diameter ($A = 1.4\times10^{12}$) can be stably trapped by the PF-AR's electron beam when it has a charge Q of up to 2.7×10^9.

The trapping condition given by Eq. (4) is also applicable to the ion-trapping phenomenon when Q is one or a few and A is the mass of the trapped ion. Note that, however, a famous solution to avoid ion trapping by prolonging the bunch spacing τ_b is generally ineffective in the case of dust trapping. Since trapped dust particles have larger A/Q than trapped ions, longer τ_b is required to avoid the trapping condition. Trapped dust particles move much more slowly than trapped ions, so dust particles are less likely to feel the gap of the bunch train.

Mass and Size of Trapped Dust

During dust trapping, bunched electrons lose their energy mainly due to the bremsstrahlung process, and those that fall out of the energy acceptance will be lost from the bunch. Assuming that a grain of dust continuously interacts with the electron beam, i.e., the amplitude of its transverse oscillation is smaller than 1σ of the beam size, we can estimate the mass of the trapped

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dust from the observed (reduced) beam lifetime [13, 14]. In other words, electron beams can tell us how many atoms should be trapped to result in the reduced beam lifetime.

The bremsstrahlung cross section σ_b is approximately given by [43]

$$\sigma_b = \frac{16 r_e^2}{3 \cdot 137} Z^2 \ln\left(\frac{1}{\Delta E/E}\right) \ln\left(\frac{183}{Z^{1/3}}\right) \quad (5)$$

where r_e is the classical electron radius (2.82×10^{-15} m), Z is the atomic number of the dust constituent, and $\Delta E/E$ is the energy acceptance.

Assuming that the electron beam composed of N_e electrons travels at the speed of light c and continuously hits dust of number density n_d (the number of atoms per unit volume), we obtain the change in the number of electrons per unit time:

$$\dot{N}_e = -N_e \sigma_b c n_d \quad (6)$$

The beam lifetime due to the bremsstrahlung τ is therefore written as

$$\tau \equiv -\frac{N_e}{\dot{N}_e} = \frac{1}{\sigma_b c n_d} \quad (7)$$

Using the atomic mass of the dust element A_{atom} and the circumference of the ring L, we derive the number density of the dust atoms n_d:

$$n_d = \frac{A}{A_{atom} 2\pi\sigma_x\sigma_y L} \quad (8)$$

Now, we summarize the above discussion and obtain the relation between the beam lifetime τ and the dust mass A:

$$\tau = \frac{A_{atom} 2\pi\sigma_x\sigma_y L}{\sigma_b c} \frac{1}{A} \quad (9)$$

More practically, the dust diameter d can be estimated by modifying the above relation:

$$\tau = \frac{12 m \sigma_x \sigma_y L}{\sigma_b c \rho} \frac{1}{d^3} \quad (10)$$

where m is the atomic mass of the dust element and ρ is the weight density of the dust material.

Note that the beam lifetime during dust trapping τ is independent of the number of electrons in the beam N_e, i.e., the stored beam current I. In other words, while the beam lifetime is being significantly reduced by the dust trapping, the product of the beam current and beam lifetime $I\tau$ is no longer constant.

Figure 1 shows the calculated beam lifetimes during dust trapping as a function of dust diameter for silica (SiO_2), titanium, and copper. At PF-AR, the natural beam lifetime is about 1200 min at 60 mA or about 2000 min at 40 mA ($I\tau$ = 70–80 A·min). Since the beam lifetime due to dust trapping at PF-AR is typically less than 500 min, the dust size is calculated to range from sub-microns to a few microns.

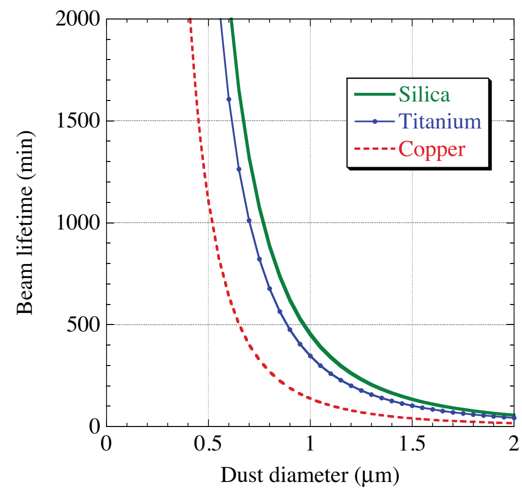

Figure 1: Estimated beam lifetimes due to dust trapping as a function of dust diameter.

Thermal Stability

Being trapped, a dust particle receives energy deposition from the beam, and consequently its temperature quickly increases. If the dust element has a low melting point or high vapor pressure, it will soon vanish. However, if the dust can survive at high temperature, the dust trapping will last a long time. In this case, the trapped dust can reach thermal equilibrium between heating by energy deposition and cooling by radiation.

In order for the trapped dust to maintain thermal equilibrium, the lifetime due to evaporation needs to be long enough. Such dust elements must have a high melting point and low vapor pressure, as discussed below.

During dust trapping, a dust particle composed of N_d atoms evaporates with a rate $\dot{N}_d$, which is given by the product of the evaporation flux and the surface area of the dust sphere:

$$\dot{N}_d = -\frac{P(T)}{\sqrt{2\pi m k_B T}} \cdot \pi d^2 \quad (11)$$

where $P(T)$ is the vapor pressure of the dust material at temperature T and k_B is the Boltzmann constant. Using the weight density of the dust material ρ, the dust lifetime τ_d is written as

$$\tau_d \equiv -\frac{N_d}{\dot{N}_d} = \sqrt{\frac{\pi k_B T}{18 m}} \frac{\rho d}{P(T)} \quad (12)$$

Lifetimes estimated using this equation for several kinds of 1-μm dust are shown in Fig. 2, together with the vapor pressures as a function of temperature [44, 45]. As one of the most stable dust elements in accelerators, a silica sphere of d = 1 μm and T = 1500 K has an estimated lifetime of 67 hours. By contrast, a copper sphere under the same condition evaporates within 2 seconds. Moreover, the copper might vanish even faster because it could be highly ionized and easily split when melted.

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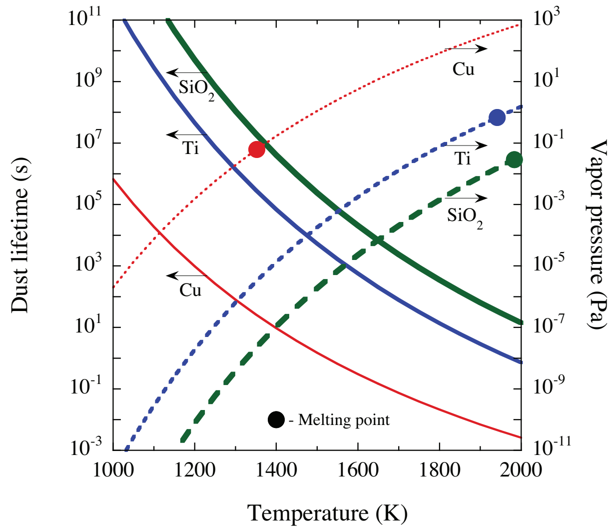

Figure 2: Estimated dust lifetimes due to evaporation as a function of dust temperature.

The size of a trapped dust particle is generally much smaller than the transverse cross section of the beam (roughly μm vs. sub-mm). The power of energy deposition on the dust particle is therefore proportional to the beam flux, i.e., the beam intensity per unit area. The minimum beam flux that surpasses the thermal radiation power from a silica sphere of 1 μm and 1900 K can be calculated as 7×10^4 A/m^2 by using the equations in Ref. [14].

Table 1 summarizes the presence of dust trapping at four large accelerators in Japan, together with their beam parameters. At PF-AR and in the single-bunch mode of PF-ring, lasting dust trapping can occur, whereas it is not observed at SPring-8 or KEKB-HER, or in the multi-bunch mode of PF-ring. This suggests that the threshold of the beam flux necessary to evaporate any ordinary dust particles could lie in the range of 10^5 A/m^2, which is nearly consistent with the above calculation result. Indeed, recent storage rings that circulate low emittance and high current beams, such as third-generation light sources and high-luminosity lepton colliders, have not been affected by dust trapping.

Table 1: Beam Parameters and Occurrence of Dust Trapping at Large Accelerators in Japan

	PF-AR	PF-ring		SPring-8	KEKB HER
		Single-bunch	Multi-bunch		
Beam current (mA)	60	20	450	100	1300
Beam emittance (nm·rad)	290	36	36	3.4	24
Beam flux (A/m^2)	2×10^4	5×10^4	1×10^6	3×10^6	3×10^6
Occurrence of lasting dust trapping	Yes	Yes	No	No	No

Known Dust Sources

Distributed Ion Pump (DIP)

A distributed ion pump installed along the beam orbit has often been identified as a source of dust [7, 17, 22, 28, 46]. Positively ionized dust particles can be released as a result of high-intensity electric discharge ("sparking" or "arcing"), and be attracted to the electron beam regardless of the polarity of high voltage applied to the pump. In some accelerators, switching the DIPs off or replacing them with non-evaporable getter (NEG) pumps improved the problems.

Figure 3 illustrates a cross-sectional view of the dipole chamber installed in PF-ring. A high voltage of −7.5 kV is applied to the titanium cathode of the DIP. The gap between the cathode and the anode is 7.5 mm, which is about 10 times wider than the criterion of high voltage breakdowns [47]. Nevertheless, dust particles are occasionally produced while the high voltage is applied.

One possible explanation for the dust production at DIPs is the famous microparticle-based breakdown hypothesis: a charge exchange between the electrodes through ionized microparticles can cause the breakdown. In fact, some experiments revealed that micron-sized particles were detected at the commencement of breakdown [48, 49].

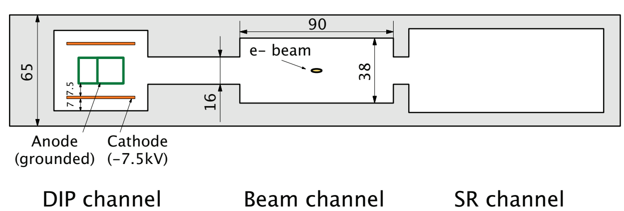

Figure 3: Cross section of the PF-ring dipole chamber.

Both at PF-ring and at PF-AR, every dipole chamber is equipped with a DIP, and during user operations we have observed dust trapping presumably caused by dust particles from the DIPs.

At PF-ring, dust trapping frequently occurred shortly after the large-scale reconstruction in 2005, at which 12 DIPs in the straight sections were replaced with new ones. It only appeared in the single-bunch mode (I = 20–60 mA), and not in the normal multi-bunch mode (I = 450 mA). As discussed earlier, the stored beam in the single-bunch mode was conceivably not intense enough to evaporate the trapped dust particles. To alleviate this problem, we switched off the newly installed DIPs during

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the single-bunch mode, and the dust trapping was completely suppressed [18]. After a few years, the DIPs in the PF-ring no longer produced harmful dust particles because of the conditioning effect.

According to dust size estimations, the diameter of dust particles should be larger than 1 μm to reduce the naturally short beam lifetime in the single-bunch mode at PF-ring. In the multi-bunch mode, however, since the natural beam lifetime is about 20 times longer than that in the single-bunch mode, a momentary drop in beam lifetime can be observed by a dust particle as small as 0.4 μm ($\sim 20^{-1/3}$).

Discharge-prone Vacuum Devices

Electric discharge can be provoked in accelerator vacuum systems not only by applied high voltage but also by beam induced electro-magnetic fields. In the latter case, the discharge source can be a sharp edge or a complicated structure in vacuum devices. For example, it was reported that sparking of the electric separators initiated dust trapping at CESR [13].

Also at PF-AR, dust trapping is sometimes caused by electric discharge at some in-vacuum type insertion devices (IDs) and at an RF kicker that has four tubal strip-line electrodes (see Fig. 4).

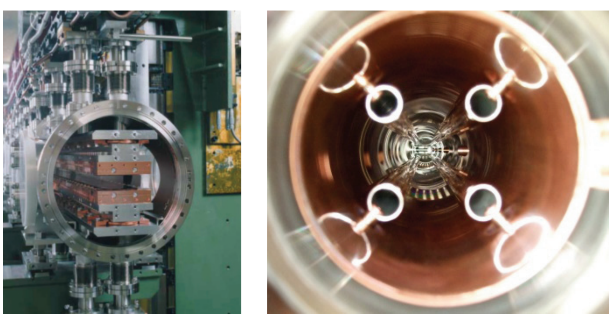

Figure 4: Discharge-prone vacuum devices at PF-AR (left: in-vacuum ID, right: RF feedback kicker).

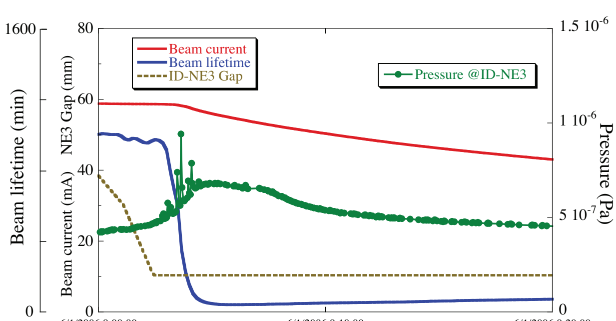

Figure 5: Example of sudden lifetime drops triggered by electric discharge at ID-NE3.

As an example of such events, Fig. 5 shows how dust production at the ID-NE3 resulted in a sudden decrease in beam lifetime. Shortly after the SR user reduced the gap from 40 mm to 10 mm, the vacuum pressure measured by a cold cathode gauge leaped several times, and then the beam lifetime suddenly dropped. We consider that the pressure spikes are evidence of electric discharges in vacuum. When such events occur at in-vacuum IDs, gamma rays are often detected at SR experiment stations.

Movable Devices

Dust particles can also be released by mechanical movement, shock, vibration, and friction in movable devices. As mentioned earlier, harmful dust particles were projected into the beam by vibration of shutters at CERN AA, and intentionally stirred up by knocking on the vacuum chamber at PEP-II HER. Also at CESR, scraper movements caused dust trapping [13].

Dust particles released by mechanical shocks or by operations of gate valves and ion pumps were carefully measured with an in-vacuum particle counter developed at CERN [50]. Using this device, they also investigated the behavior of dust particles under electric fields, and revealed that the applied high voltage released dust particles from the chamber surface.

Particles Lying on the Chamber Surface

A significant number of dust particles may exist in accelerator vacuum chambers, and, as many people suspect, are a candidate source of harmful dust. However, calculations of the forces exerted on a dust particle indicate that a positively charged dust particle lying on a conducting surface cannot be picked up because of the strong image charge force [13, 14, 28]. These particles are therefore unlikely to get trapped by the beam without any external stimulation such as shock, vibration, or electric field.

EXPERIMENTAL OBSERVATION OF THE DUST-TRAPPING PHENOMENON

Purpose of the Experiment

The dust-trapping mechanism has not been clearly elucidated even though credible theories have been developed. One of the reasons for this is a lack of experimental verification, so we conducted an experimental study designed to intentionally reproduce the dust trapping, and then carefully observed the phenomenon. Having obtained empirical evidence that electric discharges could produce dust particles, we tried to simulate such conditions using an experimental device.

Our experimental study on dust trapping had two main objectives:

1) to demonstrate that two kinds of electric discharges can provoke dust trapping:
   - discharge by applied DC high voltage (e.g. DIP)
   - discharge by beam-induced electro-magnetic fields (e.g. in-vacuum ID, RF feedback kicker)
2) to help clarify the dust-trapping mechanism by observing:
   - bremsstrahlung with gamma-ray detectors
   - dust production at electric discharges with video cameras

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Demonstration of Dust Trapping

Details of the experimental arrangements and results were described in other papers [19, 20]. Here, we only present the outline and some key results.

First, we designed a device that can simulate two kinds of electric discharges and then installed it at one of the longest straight sections in PF-AR.

As shown in Fig. 6, the device comprises two pairs of remotely controlled electrodes and two viewing ports for video cameras. Electrode A was used to simulate the discharge at a DIP by applying a high voltage of 5–7 kV to the lower electrode. Electrode B was used to simulate the discharge due to beam-induced electro-magnetic fields by moving the top and/or bottom electrodes closer to the beam (although both rods were grounded, we call them "electrodes").

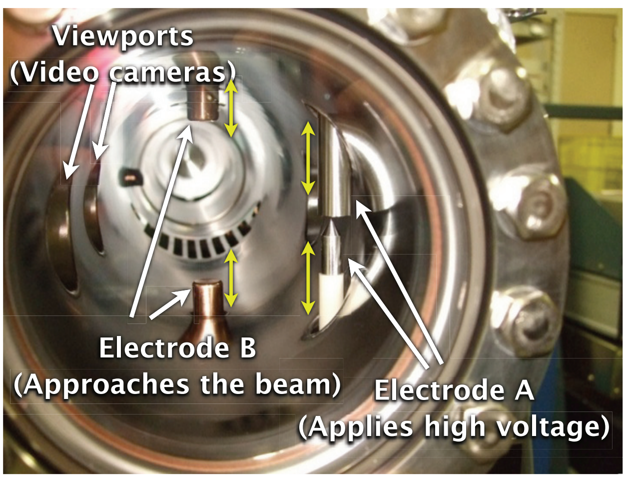

Figure 6: Interior view of the discharge device.

Throughout the experiments, Electrodes A and B were visually monitored by Cameras A and B, respectively, for evidence of electric discharges. Evidence of dust trapping was confirmed by detecting gamma-ray bursts downstream from the device, accompanied by a sudden decrease in the beam lifetime.

In the early stage of the study, the first objective was successfully achieved: intentional electric discharges at Electrode A and at Electrode B both repeatedly triggered the dust trapping. The detailed results were reported and discussed in Ref. [19].

In fact, the intentional generation of electric discharges at this device was not easy at first. For Electrode A, it was necessary to reduce the gap between the electrodes as narrow as 100 μm (from the digit counters of pulse motors). In addition, the power supply was sometimes tripped due to a short circuit, and the high voltage connector was damaged due to repeated overcurrent.

Electrode B also required a little attention. When the tip of the rod was brought to a position closer than 20 mm from the beam, the temperature outside exceeded 100ºC, even though the rods were shielded by RF contact fingers and cooled by water. On one occasion, as soon as we started to insert the rods, the beam was completely lost. A snapshot from the movie recorded by Camera B is shown in Fig. 7. Later, we found some molten fragments of the RF ringers (made of beryllium-copper, see Fig. 8) on the bottom of the device, which had probably dropped down from the top when the beam was dumped.

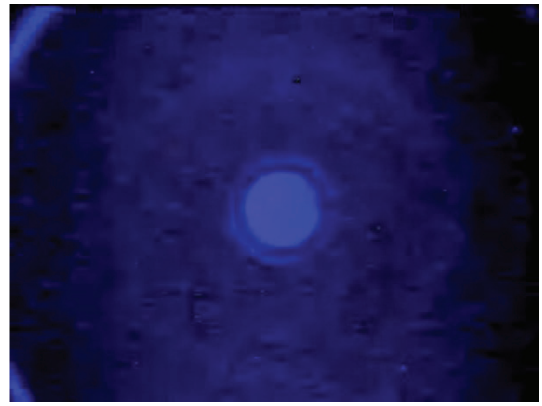

Figure 7: The moment when the beam was dumped.

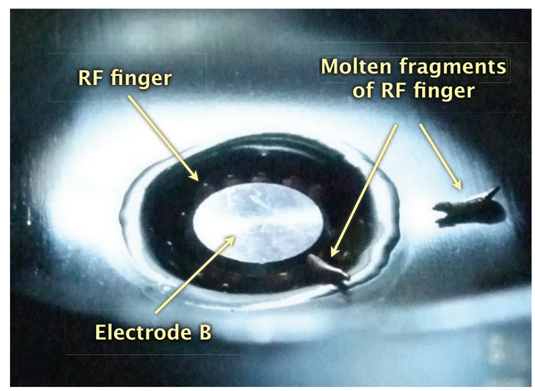

Figure 8: Molten fragments of RF fingers found on the bottom of the device.

First Direct Observation of Trapped Dust

We carried on the same dust-trapping experiment even after achieving the first purpose. In one experiment using Electrode B, the video cameras captured something that was not a common discharge image. When we started to move the pair of Electrode B, the beam lifetime suddenly dropped, i.e., the dust trapping was successfully triggered. Shortly after that, we noticed something bright moving back and forth in the displays from the cameras. The movie recorded by Cameras A and B can be seen on the web [51], and a snapshot from the movies is shown in Fig. 9.

Carefully analyzing the recorded movies, we found that the luminous object had appeared 9 times in 6 seconds, and had been moving longitudinally at a speed faster than 6 m/s or sometimes as slow as 0.3 m/s. Since it was impossible for the object to travel around the 377-m ring at these speeds within such a short period of time, the repeated appearance suggested that the object had been oscillating longitudinally in front of the cameras.

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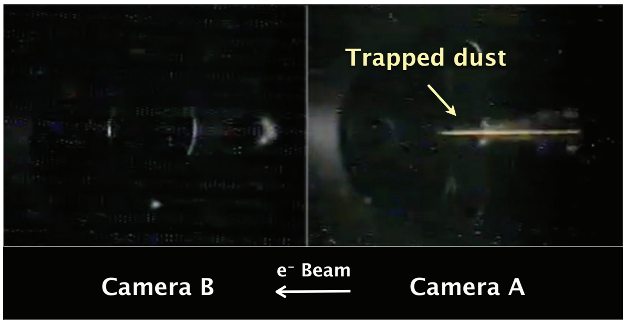

Figure 9: First direct observation of the dust-trapping phenomenon.

The period of 6 seconds at which the object appeared was almost synchronized with the period of 7 seconds at which an intense gamma-ray burst was detected. In addition, the intensity of the gamma ray was proportional to the beam loss rate. We therefore concluded that the luminous object was none other than a trapped dust particle, and visually confirmed the dust-trapping hypothesis proposed about 30 years ago.

We studied why the dust particle emitted such an intense light by calculating the number of photons entering the camera, and concluded that the trapped dust had emitted the light through blackbody radiation with a temperature higher than 1300 K. This is consistent with the theory of thermal stability. Incidentally, the dust diameter was estimated from Eq. (10) to be 1–2 μm.

The dust particle that the cameras first captured was probably released by a mechanical movement of Electrode B, because the dust trapping commenced immediately after we started to move the electrode. The distance between the beam and the electrode was long (~50 mm), and no electric discharge was observed.

Observation of Dust Trapping using Supersensitive Cameras

Estimation of the photon intensity also suggested that dust particles of smaller size and lower temperature could be observed with more sensitive cameras. Based on this expectation, we employed supersensitive cameras with about three orders of magnitude higher sensitivity than the original ones.

Discharge by DC High Voltage

The dust particle at the first direct observation was probably released by the simple mechanical movement of Electrode B. Despite repeated replication of dust trapping, the trapped dust produced by electric discharge had never been observed by normal cameras. After replacing them with supersensitive cameras, trapped dust particles were captured very frequently.

Figure 10 shows an example of dust observations in the experiment using Electrode A. After a series of sparks, a trapped dust particle appeared on the beam orbit. In this case, however, it glimmered only faintly and instantly disappeared.

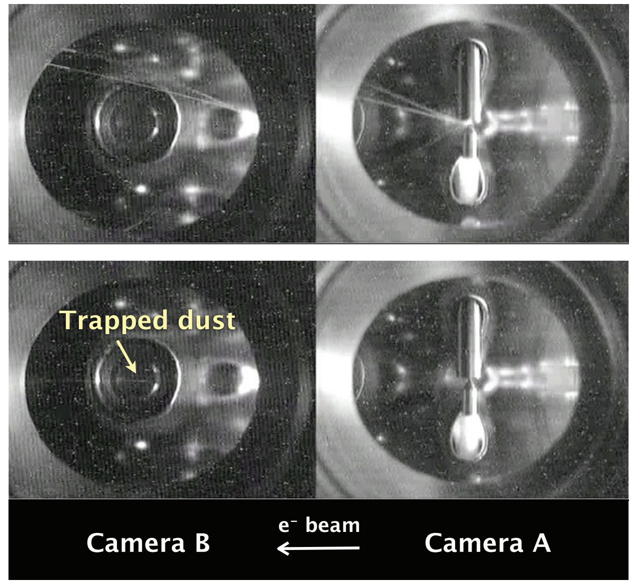

Figure 10: Direct observation of dust trapping triggered by electric discharge at Electrode A.

Discharge by Beam-induced Fields

Dust particles produced by the electric discharge at Electrode B were also seen by the supersensitive cameras. Figure 11 shows an example of such events. A spark was provoked by the beam-induced fields, and emitted a dust particle from the bottom of Electrode B. The dust seemed to collide with the stored beam and be divided into two particles (top). Immediately after that, the dust reappeared on the beam orbit (bottom).

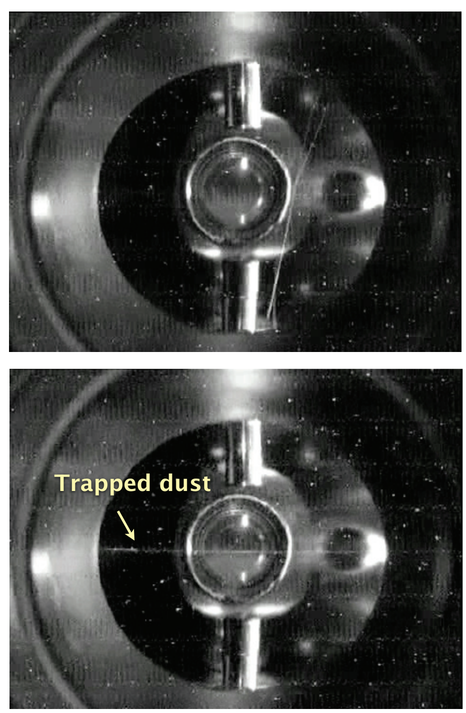

Figure 11: Direct observation of dust trapping triggered by electric discharge at Electrode B.

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Dust Trapping in a Longitudinal Potential Well

When the trapped dust was first observed, it was moving longitudinally and oscillating along the beam orbit. One possible reason for such behavior is the longitudinal potential well, also known as the ion pocket, formed by the longitudinal change in the transverse beam size and the vacuum chamber dimension.

In fact, at the first observation, Electrode B was kept moving, which could have caused a fluctuation in depth of the potential well. Based on this hypothesis, we tried to keep the electrode at the same position even after the dust release. As a result, we succeeded in confining trapped dust particles to one place right in front of the cameras.

Figure 12 is a snapshot of the movie recorded during the dust trapping. The trapped dust stayed still at almost the same position for 40 minutes until we withdrew the electrodes to the initial position.

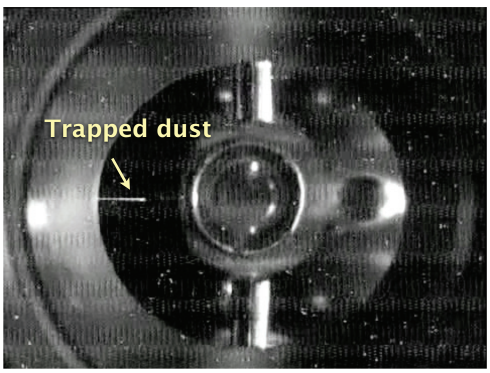

Figure 12: Direct observation of trapped dust that stayed at the same position for 40 min.

Trapping of Multiple Particles

The direct observation of dust trapping also revealed that multiple dust particles could be simultaneously trapped. While one particle was already trapped, we moved Electrode B by 1 or 2 mm to provoke an additional discharge. After the discharge, a second particle appeared and was stably trapped next to the original one as shown in Fig. 13.

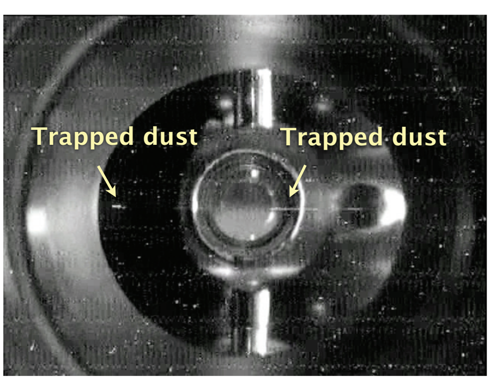

Figure 13: Direct observation of multiple dust particles being trapped simultaneously.

SUMMARY

Dust trapping is an intrinsic problem in electron storage rings. It can significantly reduce the performance of accelerators by giving rise to a sudden decrease in the beam lifetime and by emitting bremsstrahlung gamma-rays into experimental detectors. Since the first appearance of the phenomenon in the early 1980s, many studies have been done and some reasonable theories have been developed.

Thanks to these efforts, it is now commonly accepted that, for example, electric discharges in vacuum can produce dust particles, and that thermally stable dust particles can reach thermal equilibrium. The latter theoretical understanding explains why recent high-current and low-emittance electron storage rings are not affected by dust trapping.

At PF-AR, long-term investigation has led to evidence that dust particles can be produced at DIPs and discharge-prone vacuum devices. This empirical information was experimentally demonstrated by using a discharge device as the dust source.

In one experiment, video cameras fortuitously captured the trapped dust particle as a luminous object, by which the dust-trapping hypothesis was first visually confirmed. In addition, detailed analysis of the cause of the light emission concluded that the temperature of the trapped dust exceeded 1300 K, which supports the main dust-trapping theory.

Further observations using supersensitive cameras indicated that the trapped dust moved or stayed in a longitudinal potential well. Thus, we found that direct observation of dust trapping is a useful method to investigate the various behaviors of trapped dust particles.

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