TRAPPED MACROPARTICLES IN ELECTRON STORAGE RINGS *

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Abstract

Sudden drops of the beam lifetime ascribed to the capture of positively charged macroparticles (‘dust’) are observed at many high-energy electron storage rings. A trapped macroparticle has a certain thermal lifetime due to energy transfer from the beam; the interplay of different ionizing and discharging processes gives rise to an equilibrium charge. The beam lifetime is reduced by bremsstrahlung both in the field of the atomic nuclei and in the macroscopic field of the highly charged dust particle. Recent observations at some storage rings can be explained by the capture of a single macroparticle of about micron size, possibly made from silicon dioxide. In the two B factories under construction, PEP-II and TRISTAN-II, trapped macroparticles will be thermally unstable and explode after a few tens of microseconds, thanks to the much higher beam current as compared with other storage rings.

I. INTRODUCTION

Sudden beam loss phenomena, which are ascribed to the capture of positively charged macroparticles of typically micron-size, have been observed in many electron and antiproton storage rings: for example in the TRISTAN accumulation ring [1]; in DCI and Super-ACO [2]; in CESR [3]; in the ESRF storage ring [4]; and in the CERN Antiproton Accumulator [5]. A dust problem is even reported from AdA as early as 1961 [6]. More recently, in 1992 and 1993, the HERA electron ring at DESY has suffered from regular sudden drops of the electron beam lifetime down to 15–60 minutes that have limited the beam current for luminosity runs to values of about 20 mA. A similar phenomenon has been seen at DORIS-III. While in HERA neither a coherent nor an incoherent tune shift could be measured, the lifetime drops coincided with strong localized losses of electrons as a result of bremsstrahlung in certain regions of the machine. The effect is related to the operation of distributed ion pumps, suggesting that macroparticles are generated and ejected from the pumps which are illuminated by (scattered) synchrotron radiation. Both DESY rings are now being operated with positrons rather than electrons and beam-lifetime drops are no longer observed. The successful operation of B factories like PEP-II, under construction at SLAC, or TRISTAN-II, being built at KEK, requires electron currents of 1 A or above a factor 50 higher than what has been achieved in HERA. The higher current is an advantage since, unlike in HERA, trapped macroparticles are expected to melt and explode within a few tens of microseconds. In this report, a possible theory of dust trapping is described. Section II discusses the dynamic and thermal stability of a trapped macroparticle as well as its equilibrium charge. The resulting beam lifetime is calculated in Section III. Section IV is devoted to two different sources of dust: emission from distributed ion pumps and pick-up from the bottom of the beam pipe. In Section V, the theory is applied to HERA, and predictions are made for PEP-II and TRISTAN-II. The results are summarized in Section VI.

II. STABILITY AND CHARGE

In most electron storage rings, single-atomic ions are overfocused and lost in a bunch gap [7]. Only macroparticles whose equilibrium mass-to-charge ratio is sufficiently large can be stably trapped. The minimum ratio required, as determined by simulations, is of the order $A/Q \approx 10^3 - 10^4$, for both HERA and the PEP-II HER. Here, A denotes the mass of the macroparticle in units of the proton mass m_p and Q is the charge in units of the electron charge. We shall see that this condition is easily fulfilled for the estimated masses and equilibrium charges in HERA. A more difficult problem than the dynamic is the thermal stability. Simulations indicate that, once a macroparticle comes close to the beam and is trapped, its transverse oscillation is damped to amplitudes below 1 $\sigma_{x,y}$ in less than a half period of oscillation. The damping is due to ionization and discharging processes. The beam electrons ionize the atoms of the dust particle and thereby deposit a considerable amount of energy. Because high-energetic secondary electrons escape from the charged dust particle, for typical parameters, the total energy deposited is about five times less than the naive estimate based on the Bethe-Bloch result, but still about five to ten times larger than the effect of the incident synchrotron radiation. The energy deposition from the beam is approximately

$$\left.\frac{\Delta E}{\Delta t}\right|_{ion} \approx \frac{1}{5}\frac{2R^3 N_{el}^{tot} f_{rev}\rho}{3\sigma_x\sigma_y}\left.\frac{dE}{dx}\right|_{\min} , \qquad (1)$$

where ρ denotes the mass density of the particle, R its radius, $\sigma_{x,y}$ the rms beam size, N_{el} the total number of beam electrons, f_{rev} the revolution frequency and $dE/dx|_{\min} \approx 1.5$ MeV cm^2 g^{-1} the energy loss of minimum-ionizing particles. The initial temperature rise is exceedingly fast, of the order 10^5–10^8 K/s. If it is not balanced by heat radiation, the dust particle explodes when its temperature reaches the melting point, since it simultaneously acquires a significant charge (see later). Assuming a homogeneous surface charge, a molten particle is stable if

$$4\pi R^2\gamma_{surf} > \frac{Q^2e^2}{8\pi\epsilon_0 R} \quad \text{or} \quad \frac{A}{Q^2} > \frac{r_p c^2\rho}{6\gamma_{surf}} \approx 50\text{–}150 , \qquad (2)$$

where r_p denotes the classical proton radius, γ_{surf} the surface tension, c the velocity of light, and ρ the mass density of the dust particle. Usually this condition is not fulfilled and thus particles are thermally stable only when their equilibrium temperature is below the melting point. The heat radiation of small particles is

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reduced, since, roughly, a particle radiates only at wavelengths smaller than its size. The absorption coefficient for simple geometries can be calculated by Mie theory, for instance using the program BHMIE of Ref. [9]. The calculation involves the complex frequency-dependent dielectric constant of the respective material. The balance of energy deposition and heat radiation determines the equilibrium temperature T which depends on the material, mass, and geometry. A larger surface-to-volume ratio leads to a decreased temperature. At temperature T the evaporation rate $\dot{A}$ of the particle and its thermal lifetime τ_{th} are given by

$$\dot{A} \approx -\frac{4\pi A_{atom}}{\sqrt{2\pi m_p A_{atom} k_B}} \left(\frac{3m_p}{4\pi\rho}\right)^{\frac{2}{3}} \frac{p(T)\ [Pa]}{\sqrt{T}} A^{\frac{2}{3}} \qquad (3)$$

and $\tau_{th} \equiv A/|\dot{A}|$, where $p(T)$ is the vapor pressure, and A_{atom} the atomic mass of the material. A trapped macroparticle gets rapidly ionized by the beam, until discharging effects become so strong that some equilibrium is reached. For large values of Q the ionization rate, due to escaping secondary electrons, is

$$\dot{Q}_{ioniz} \approx 4 \cdot 10^{12} \mathrm{s}^{-1} \frac{N_{el}^{tot} f_{rev} \rho}{\sigma_x \sigma_y} \cdot \frac{R^4}{Q}, \qquad (4)$$

where r_e is the classical electron radius, m_e the electron mass, N_A Avogadro's number, and SI units are used. One discharging effect is the capture of photoelectrons which are created by photoemission from the vacuum chamber wall [3]. For high charge and high temperature, a different discharging process will dominate, namely the field evaporation of ions. It is described by the equation [10]

$$\dot{Q}_{ev} = -\frac{A_{atom} m_p 8\pi^2 R^2 k_B^2}{h^3} T^2 \exp\left(-\frac{U + V - \Phi_-}{k_B T} + \frac{e^2\sqrt{Q}}{4\pi\epsilon_0 R k_B T} - \frac{1}{k_B}\int_0^T \frac{dT'}{T'^2}\int_0^{T'} dT''\, C_p(T'')\right), \qquad (5)$$

where C_p is the heat capacity at constant pressure, U and V the ionization and vaporization energy, respectively, and Φ_- the work function of the material.

III. BEAM LIFETIME

If the beam loss is caused by bremsstrahlung in the field of the nuclei of the macroparticle, the beam lifetime τ_b^n is [11]

$$\frac{1}{\tau_b^n} \approx \left(\frac{16 r_{el}^2}{3 \cdot 137} \ln\frac{E_e}{\Delta E_e} \ln\frac{183}{(Z_{atom})^{\frac{1}{3}}}\right) \cdot \frac{c A (Z_{atom})^2}{A_{atom} 2\pi \sigma_x \sigma_y C} \qquad (6)$$

where $\Delta E_e/E_e \approx 0.01$ is the energy acceptance, Z_{atom} the atomic number, and C the ring circumference. Provided that the equilibrium charge is high enough, bremsstrahlung can also take place in the electric field of the charged dust particle as a whole. This process is similar to the beamstrahlung in linear colliders and may be called "duststrahlung." It can be characterized by a dimensionless parameter Υ [12] which—for a needle-shaped dust particle of transverse radius R and length h, aligned in the beam direction—reads:

$$\Upsilon(b) \approx \frac{\hbar c \gamma^3}{\rho E_e} \approx \frac{\hbar \gamma e^2 Q}{m_e^2 c^3 2\pi\epsilon_0} \frac{\min(b/h, 1)}{\max(R, b)^2}\ . \qquad (7)$$

The term $\rho \approx (E_e \max(b, h))/(c\Delta p_\perp)$ is the local bending radius and $\Delta p_\perp \approx (2Qe^2)/(4\pi\epsilon_0 c) \cdot \min\left(\frac{1}{b}, \frac{b}{R^2}\right)$ is the transverse momentum transfer for impact parameter b. The average number $N_\gamma(b)$ of emitted photons per electron and per revolution time is $N_\gamma(b) \approx \frac{5}{2\sqrt{3}} \frac{c\alpha\Upsilon(b)}{\lambda_e \gamma} / (1 + \Upsilon(b)^{\frac{2}{3}})^{\frac{1}{2}} \cdot \frac{\max(b,h)}{c}$, where we have multiplied the rate of photons per unit time [12] by $\Delta t \approx \frac{\max(b,h)}{c}$. For impact parameters b smaller than $b_{\max}$ defined by $\Upsilon(b_{\max}) = 0.02$ the typical photon energy is so high that each photon emission leads to an electron loss. The beam lifetime τ_b^{ds} due to duststrahlung is

$$\frac{1}{\tau_b^{ds}} \approx \pi \int_0^{b_{\max}} N_\gamma(b)\, b\, db \cdot \frac{c}{2\pi\sigma_x\sigma_y C}. \qquad (8)$$

IV. ORIGIN OF DUST

If charged macroparticles are generated by a vacuum arc inside the (horizontal) distributed ion pumps, they may be accelerated in the direction of the pump slots by the applied voltage U_p (about 5 kV in HERA). Dependent on their initial velocity the macroparticles may or may not be trapped by the beam. One condition for capture is that the particle has not fallen by more than about 8 vertical σ_y when it reaches the horizontal beam position. (The factor 8 comes from a simulation.) For HERA, this condition translates into $A/Q_0 \leq 4 \cdot 10^{10}\, U_p/\mathrm{kV}$, where Q_0 is the initial charge. A second condition is that the particle is ionized highly enough during its first beam crossing. Again, for HERA, it reads $A^{\frac{11}{6}}/Q_0^{\frac{5}{2}} \geq 1.5 \cdot 10^{12} (U_p/\ \mathrm{kV}\ )^{\frac{3}{2}}$.

Three forces act on a dust particle at the bottom of the vacuum chamber: (1) the attractive force by the beam $F_{beam} \propto Q$ is counteracted by (2) gravity $F_{grav} \propto A$ and, for a conductive chamber surface, by (3) the image charge force $F_{image} \propto Q^2/A^{\frac{2}{3}}$ [3]. Due to the different dependences on mass and charge of the three forces, it is impossible for the beam to pick up any dust particles from the bottom of the beam pipe in most existing storage rings.

V. HERA AND B FACTORIES

In HERA, most metal particles, e.g., those made from copper or aluminum, will explode within a few milliseconds after capture. Needle-shaped titanium particles do not explode, because of their high melting point, but evaporate within about 100 s. More stable is silicon dioxide, which was found in the HERA pumps. Assuming the same complex dielectric constant as for vitreous silica [13], its heat radiation is strongly enhanced at high temperature.

As an example, (see Fig. 1), for a mass $A = 10^{14}$ (or radius $R \approx 2-2.5\ \mu$m), the thermal lifetime of a titanium needle is 17 s ($T \approx 1750$ K), while that of a needle-like silica particle is 6 hours ($T \approx 1440$ K). An emissivity $\epsilon \approx 0.5$ is assumed. The lifetime of silica is higher partly due to the smaller temperature and partly due to a much lower vapor pressure. Figure 1 demonstrates that the thermal lifetime increases for decreasing mass until it reaches a maximum at $A \approx 3 \cdot 10^{11}$–$10^{13}$. For smaller mass, the lifetime is shorter due to the reduced heat radiation. The most stable silica particles of mass $A \approx 3 \cdot 10^{11}$ are predicted to melt at a beam current of about 800 mA for a beam energy of 26 GeV, or at 170 mA for 12 GeV. Equation (6) shows that a beam lifetime

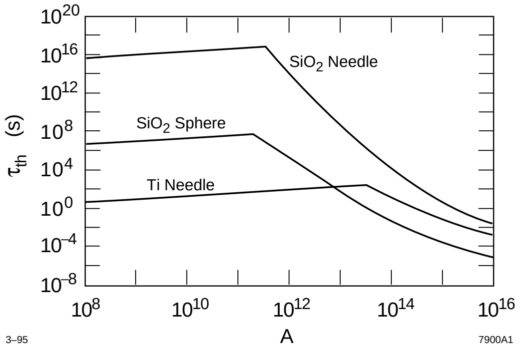

Figure. 1. Thermal lifetime τ_{th} of trapped macroparticles in the HERA electron ring as a function of mass.

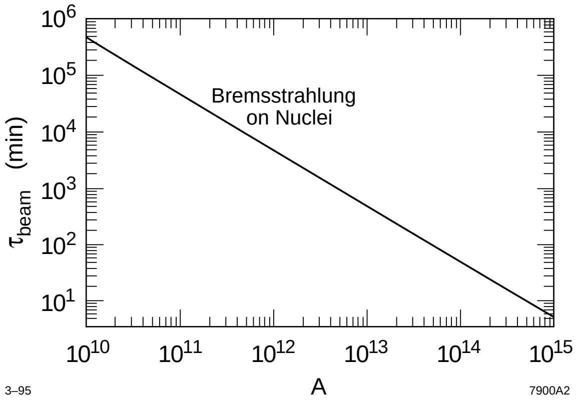

Figure. 2. Predicted beam lifetime in the HERA electron ring as a function of macroparticle mass.

of $\tau_b^n \approx 50$ min. is caused by a trapped silica particle of mass $1.6 \cdot 10^{14}$ ($R \approx 3$ μm). After 0.3 s such a particle has acquired its equilibrium charge of $4 \cdot 10^8$, using Eqs. (4) and (5). For this charge the effect of duststrahlung is insignificant. Figure 2 shows the expected beam lifetime in HERA as a function of the macroparticle mass. Due to the higher operating current in TRISTAN-II and PEP-II, even a trapped silica particle will melt after about 10 μs and 50 μs, respectively. For $A \approx 10^{14}$ the acquired charge at this moment is $Q \approx 5 \cdot 10^7$, so that the particle will explode according to Eq. (2). In the current PEP-II design, the slots of the distributed ion pumps are tilted so as to reduce the incidence of scattered radiation into the pump and to prevent the emission of macroparticles.

VI. CONCLUSIONS

A possible theory of dust trapping was described which seems consistent with the observations at HERA. Application of this theory to PEP-II and TRISTAN-II suggests that dust trapping will not be a problem in these storage rings. However, most of the results presented are quite sensitive to material constants at high temperature and to physical properties of charged hot macroparticles which are either not readily available or not exactly known.

VII. ACKNOWLEDGMENTS

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