3.6 Beam Lifetime

Beam lifetime in the storage ring is dominated by three beam loss-processes: the quantum excitation, intra-beam scattering (Touschek effect), and scattering off of residual gas molecules (elastic and inelastic). The individual loss mechanisms contribute to the beam total lifetime according to the relation

$$\frac{1}{\tau} = \frac{1}{\tau_{quantum}} + \frac{1}{\tau_{Touschek}} + \frac{1}{\tau_{elastic}} + \frac{1}{\tau_{inelastic}} \tag{3.6.1}$$

The total beam lifetime τ defines the time when the beam current to reduce by a factor of e=2.718.

3.6.1 Quantum Lifetime.

As a result of quantum emission and radiation damping, the electron bunches have a 3-dimensional Gaussian distribution. The far tail of the distribution will be truncated by the longitudinal or transverse acceptance of the storage ring, leading to beam losses. The electron beam lifetime due to the quantum character of synchrotron radiation is given by

$$\tau_{\mathrm{q}} = \frac{\tau}{2} \frac{e^{\xi}}{\xi}, \tag{3.6.2}$$

where $\xi = (A/\sigma)^2/2$, τ is the damping time; A is the transverse acceptance of the beam for the transverse case and the RF acceptance for the longitudinal case, σ - is the rms emittance for the transverse case and rms energy spread for the longitudinal case. Typically the physical aperture is much larger than transverse size of the beam. The RF amplitude is chosen to be high enough to strictly compensate for the energy loss to synchrotron radiation and providing sufficient energy acceptance for the beam. The range of energy acceptance for the CANDLE storage is at the level of 2-2.5% with an overvoltage factor of 2.45 for a fully populated with insertion devices.

For an electron beam with a rms emittance of 8.4 nm-rad and a rms energy spread of 0.1%, the quantum lifetimes of electron beam in all three dimensions are larger than 10^{38} hours, or essentially infinite.

3.6.2 Intra-beam Scattering (Touschek lifetime).

The high bunch densities in low emittance electron storage rings lead to an enhanced rate of elastic collisions between electrons within the bunch. This Coulomb scattering of charged particles in a stored beam causes an exchange of energies between transverse and longitudinal motions and is referred to a Touschek effect. When the small transverse momentum of the particles is transferred into a large longitudinal momentum due to scattering, the energy change may be large resulting in bunch particle scattered outside the RF bucket or the momentum aperture of the lattice and be lost. The average Touschek lifetime is determined by the bunch volume, the bunch current, and the energy acceptance and is given by

$$\tau_T = \frac{8 \cdot \pi \cdot \sigma_x \cdot \sigma_y \cdot \sigma_s \cdot \gamma^2 \cdot \delta_{RF}{}^3}{\mathrm{N} \cdot r_e{}^2 \cdot c \cdot D(\nu)} \tag{3.6.3}$$

where $\sigma_{x,y,s}$ are the bunch average dimensions, γ is the relativistic factor, δ_{RF} is the energy acceptance, N is number of particles per bunch, r_e =2.82 10^{-15} m is the classical electron radius, c is the speed of light, $D(\nu)$ is the smooth dimensionless function of ν and varies for CANDLE with a range of 0.2-0.3. For a circulating current of I = 350 mA, the number of particles per bunch is $N = 5.6 \cdot 10^9$ (0.9 nC) assuming 282 RF buckets of the total 360 are filled. The rest 78 buckets are provide the necessary gap for ion clearing. For an energy of 3 GeV and a RF energy acceptance of 2.376%, the average Touschek lifetime over the ring is then about 39 hours.

For an actual beam, the variation of the beam envelope, i.e. the derivatives of the horizontal and vertical amplitude functions and dispersion, should be taken into account in evaluating the particle loss rate variation along the lattice. The formula for the Touschek lifetime is then modified to

$$\tau_T = \frac{8\pi\gamma^2\sigma_s\sigma_x\sigma_y\delta_m{}^2}{r_p^2 cN_p} G(\delta_m, \beta_x, \beta_y, \eta) \tag{3.6.4}$$

where the form-factor G is a function of the amplitude functions, dispersion and energy acceptance of the ring [1].

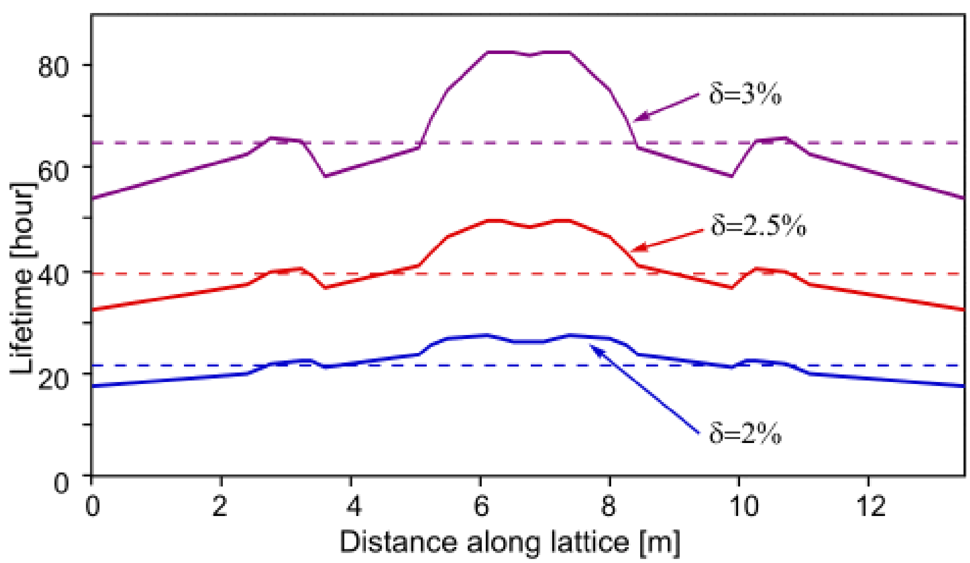

Fig. 3.6.1 Touschek lifetime evolution along the lattice for various energy acceptances (solid line). The dashed lines show the average lifetimes.

Fig. 3.6.1 presents the Touschek lifetime evolution along the magnetic lattice of the storage ring for different energy acceptance (solid lines). Dashed lines represent the corresponding lifetimes averaged over the ring.

The simulation results of the Touscheck lifetime averaged over the lattice period for different energy acceptance of the ring is given in Table 3.6.1.

Table 3.6.1 Average lifetimes.

δ_{RF} (%)	τ_{Tousch} (hour)
2	21.9
2.5	39.5
3	64.9

Fig.3.6.2 shows the Touschek lifetime dependence upon the emittance coupling value for different energy acceptance values. In particular, for a coupling of 2% and energy acceptance of 2.376% the Touscheck lifetime is at level of 54.15 hours.

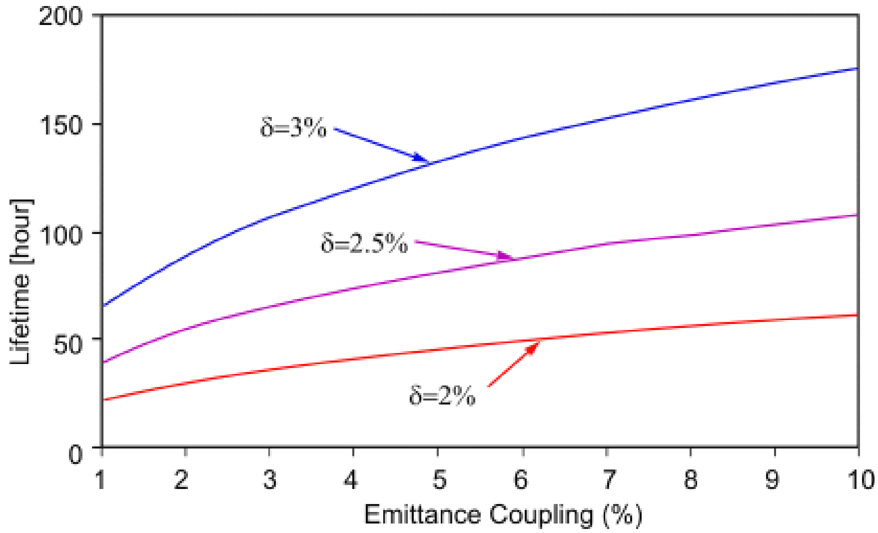

Fig.3.6.2 Averaged Touschek lifetime vs emittance coupling and energy acceptance.

3.6.3 Residual Gas Scattering.

The interaction between beam particles and residual gas molecules consist of two main mechanisms: elastic (Rutherford) scattering and inelastic (Bremsstrahlung) scattering.

Elastic scattering. The beam lifetime due to Rutherford elastic scattering for the residual gas pressure P is given by [2,3]:

$$\frac{1}{\tau_{el}[s]} = \frac{4\pi r_e^2 c N_A}{R\gamma^2} \frac{\langle \beta_y \rangle}{A_y[m \cdot rad]} \frac{P[Pa]}{T} \sum_i^n Z_i (Z_i + 1) N_i r_{p_i} \tag{3.6.5}$$

where N_A is Avogadro's number, $R = 8.314\, J/(K \cdot mol)$ is the universal gas constant, $T[^\circ K]$ is the residual gas temperature, $\langle \beta_y \rangle = 10.2m$ is the average vertical beta function, $A_y = (g/2)^2 / \beta_y = 10mm \cdot mrad$ is the vertical acceptance at insertion [4], g is the ID gap, n is the residual gas partial components number, r_{p_i} - partial fraction of the residual gas components, Z_i - atomic number, N_i - number of atoms per molecule.
In practical units we get:

$$\frac{1}{\tau_{el}[h]} = 0.272 \frac{P[nTorr]}{T[^\circ K] \cdot E^2 [GeV^2]} \frac{\langle \beta_y \rangle [m]}{A_y [mm \cdot mrad]} \sum_i^n Z_i (Z_i + 1) N_i r_{p_i} \tag{3.6.6}$$

If we assume that the residual gas composition to be equivalent to nitrogen gas N_2 ($n = 1, r_{p_1} = 1, Z_1 = 7$, $N_1 = 2$ and $Z_1(Z_1 + 1) \approx Z_1^2 \approx 49$) at $T = 273^\circ K$ then the beam lifetime is given by [5]

$$\tau_{el}[h] = 10.25 \frac{E^2 [GeV^2] \cdot A_y [mm \cdot mrad]}{\langle \beta_y \rangle [m] \cdot P[nTorr]} \tag{3.6.7}$$

For $P = 1\, nTorr$ pressure in the vacuum chamber, the lifetime due to elastic scattering is then $\tau_{el} = 91.4$ hours. For a residual gas composition of $80\% H_2$ and $20\% CO$ ($Z_1 = 1, N_1 = 2, r_{p_1} = 0.8$, $Z_2 = 7, N_2 = 2, r_{p_2} = 0.2$) the lifetime is $\tau_{el} = 329.2\ hours$.

The dependences of the elastic scattering lifetimes on the residual gas pressure are given in Fig. 3.6.3 (residual gas N_2) and Fig. 3.6.4 (residual gas $80\%H_2+20\%CO$) for different gap values. The comparison of the results shows that the lifetime depends strongly on the residual gas composition. Typically the main residual gases in a storage ring are H_2 and CO the lifetime is dominated by CO gas rather than H_2 gas in spite of the lower partial pressure of CO. It is important to increase the ratio of H_2 to CO gas to improve the beam lifetime.

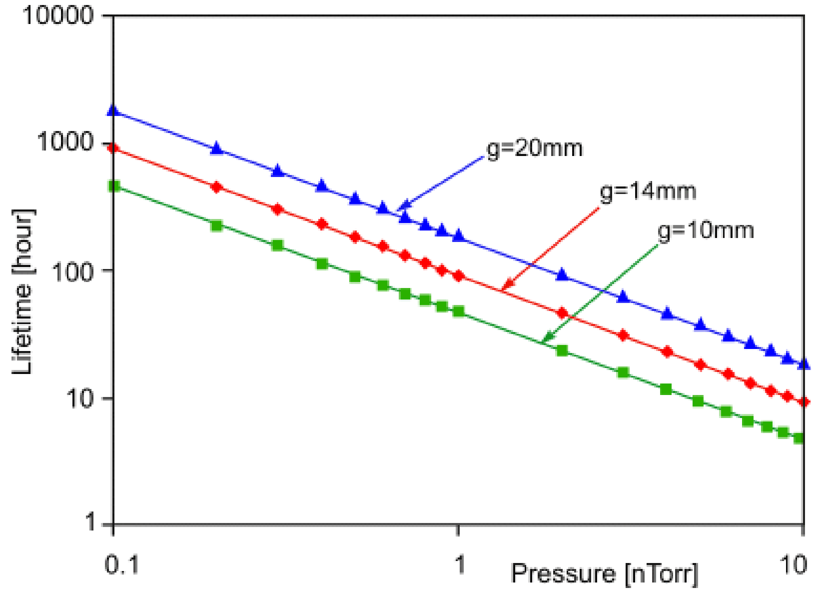

Fig. 3.6.3. Elastic scattering lifetime vs pressure for various gaps. Residual gas N_2.

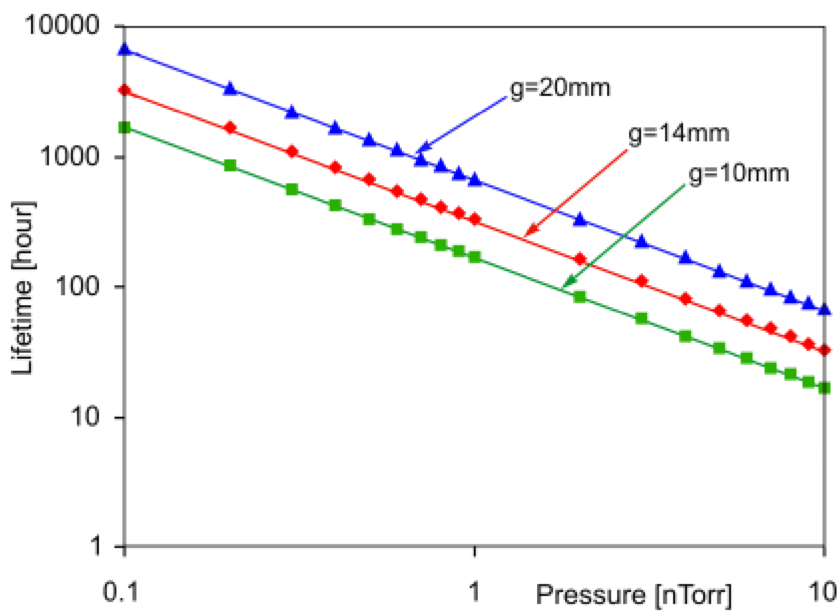

Fig. 3.6.4 Elastic scattering lifetime as a function of pressure for various gap values. Residual gas composition is $80\%H_2+20\%CO$

Inelastic scattering. Inelastic scattering (Bremsstrahlung) is an effect of deceleration and photon emission due to beam interaction with the residual gas atoms. The lifetime due to bremsstrahlung is given by [6]:

$$\frac{1}{\tau_b[s]} = \frac{4r_e^2 cN_A}{137R} L(\delta_{RF}) \ln\frac{183}{\sqrt[3]{Z}} \frac{P[Pa]}{T[^\circ K]} \sum_i^n Z_i(Z_i+\xi)N_i r_{p_i} \tag{3.6.8}$$

with

$$\xi = \ln\left(1440Z^{-2/3}\right)/\ln\left(183Z^{-1/3}\right), \qquad L(\delta_{RF}) = \frac{4}{3}\left(\ln\frac{1}{\delta_{RF}} - \frac{5}{8}\right)$$

In practical units we get

$$\frac{1}{\tau_b[h]} = 2.42\cdot 10^{-3} L(\delta_{RF}) \ln\frac{183}{\sqrt[3]{Z}} \frac{P[nTorr]}{T[^\circ K]} \sum_i^n Z_i(Z_i+\xi)N_i r_{p_i} \tag{3.6.9}$$

The inelastic scattering lifetime is 233 hours for 80%H_2+20%CO gas composition and 55.4 hours for cases of only N_2 (or CO) residual gas at P=1 nTorr and T=273$^\circ K$. The lifetime dependence on the pressure for these two different compositions of the residual gas is given on Fig.3.6.5.

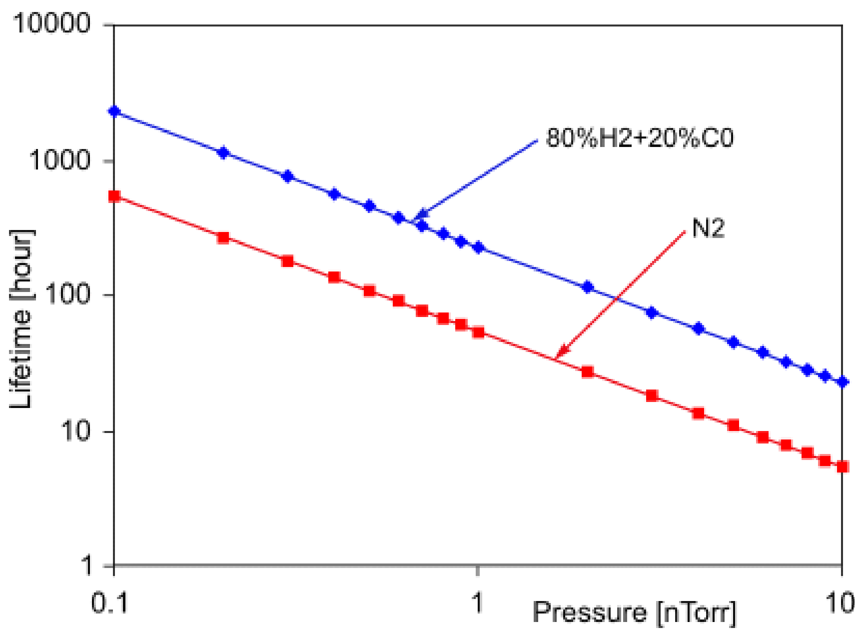

Fig. 3.6.5 Bremsstrahlung lifetime, as a function of pressure and residual gas species.

As indicated in Figure 3.6.5, the dependence of the Bremsstrahlung lifetime on a residual gas species is similar to the elastic scattering of beam particles on the residual gas.
The summary of the electron beam lifetimes in CANDLE storage ring is given in Table 3.6.2 based on the conservative approach on the residual gas composition (N_2).

Table 3.6.2 Storage ring electron beam lifetimes.

Electron Beam Energy (GeV)	3
Electron Beam Current (mA)	350
Gap Voltage MV	3.3
Energy Acceptance %	2.376
RMS bunch length (mm)	6.5
Average horizontal beta, m	5.22
Average vertical beta, m	10.56
Coupling (%)	1
N_2 equivalent gas pressure (nTorr)	1.0
Beam lifetimes Elastic scattering (hours) Inelastic scattering (hours) Touschek lifetime (hours) Quantum lifetime (hours)	 91.4 55.4 39.5 $>10^{38}$
Total lifetime (hours) 1% coupling 2% coupling	 18.4 21.4

An integrated beam lifetime in storage ring is at the level of 18.4 hours with the 1% coupling of the horizontal and vertical oscillations.

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