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RESIDUAL GAS LIFETIME IN HIGH ENERGY PHOTON SOURCE (HEPS)

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Abstract

High vacuum has always been mandatory in particle accelerators. This is especially true for circular machines, where the beam makes thousands or millions turns, and beam lifetime is heavily affected by the residual gas scattering. At the beginning of storage ring operation the lifetime was very short mostly dominated by residual gas scattering. The residual gas lifetime is comprised of the elastic and inelastic scattering on electrons and elastic and inelastic scattering on nuclei. One usually calculates only the elastic scattering on nuclei (single Coulomb scattering) and inelastic scattering on nuclei (bremsstrahlung) of the residual gas scattering lifetime component. The analytic calculation the residual gas scattering lifetime and simulations of the beam interaction with the residual gas with code will be shown in this presentation.

INTRODUCTION

The beam loss in electron storage rings depends to a large extent on the interaction of the beam with heavier residual gas molecules due to bremsstrahlung and Coulomb scattering. During the initial commissioning severe limitations on the achievable beam current were observed due to large pressure rises and very short beam lifetime.

When electrons collide with extra nuclear electrons and nuclei of the residual gas, they may undergo a momentum change, which might exceed the RF momentum acceptance or, the electrons experience an angular deflection which induces a betatron oscillation which may also exceed the aperture limited by the vacuum chamber or dynamic aperture.

ELASTIC GAS SCATTERING LIFETIME

Due to the elastic scattering of electrons with the residual gas atoms, the electrons get deflected and the amplitude of betatron oscillation increases. If the amplitude of betatron oscillation is more than the dynamic aperture or physical aperture of the vacuum chamber the storage ring, electrons get lost. The residual gas lifetime due to elastic scattering of the stored electrons with the nuclei of residual gas atoms $\tau_{u,el}$ is[1][2] :

$$\frac{1}{\tau_{u,el}[s]} = \frac{2\pi r_e^2 c N_A}{R\gamma^2} \frac{\beta_u}{A_u[\text{m}\cdot\text{rad}]T} \sum_{atom,j}\left(Z_j^2 \sum_{gas,j} \alpha_{ij} P_i [Pa]\right) \tag{1}$$

where r_e is the classical electron radius (2.8×10^{-15} m), c is the speed of light, N_A is the Avogadro's number, Z is the atomic number of the residual gas species, γ is the relativistic factor of the electrons in the stored beam, β_u is the beta function at the limiting aperture and A_u the limiting aperture, P is the pressure in the vacuum chamber, R = 8.314 J/(K*mol) is the universal gas constant, α is partial fraction of the residual gas components.

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From the formula (1) can see, the elastic gas scattering lifetime depends on residual gas composition and the storage ring's acceptance. For a residual gas composition of 80% H_2 and 20%CO, the elastic gas scattering lifetime of the High Energy Photon Source(HEPS) [3] is about 300 hours for 1 *nTorr* pressure with the dynamic aperture as show in Figure 1.

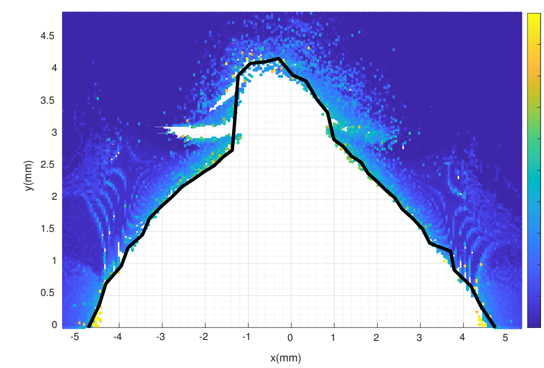

Figure 1: Dynamic aperture at injection point.

Considering the magnetic field error and misalignment effect on the dynamic aperture, 200 random error seeds were used for dynamic aperture tracking at injection point as show in Figure 2 and the results of elastic gas scattering lifetime are shown in Figure 3. Take the tenth-lowest set as the reference standard, the elastic gas scattering lifetime with error effects is about 180 hours.

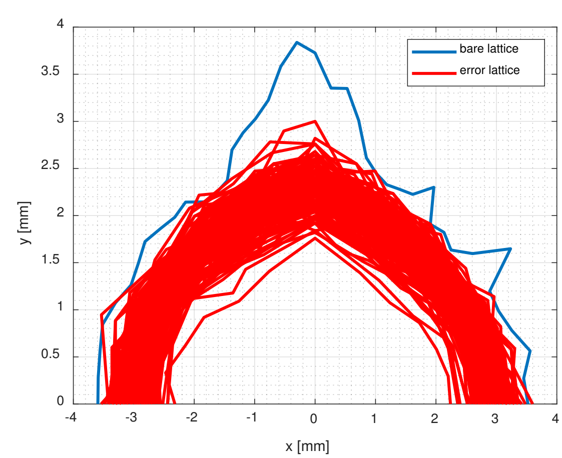

Figure 2: Dynamic aperture of injection point with errors.

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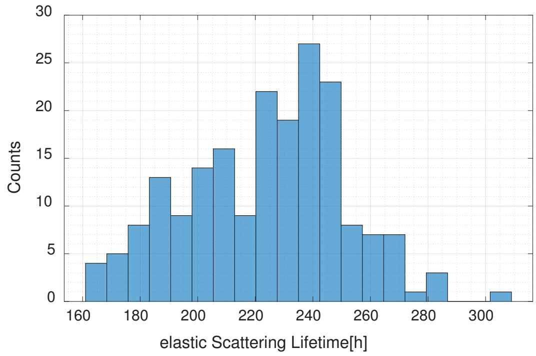

Figure 3: Distribution of elastic scattering lifetime of residual gas (200 random error seeds).

Elastic scattering on nuclei of the residual gas leads to an angular kick for the betatron motion. We use the accelerator simulation soft ELEGANT [4] to add relatively realistic physical apertures of HEPS lattice as follow and shown in Figure 4：

- Normal vacuum chamber: circular (11mm*11mm)
- low-beta straight sections: rectangular (10mm*2.5mm)
- high-beta straight sections: ellipse (11mm*4mm)
- Lamberson section: ellipse (11mm*2.5mm)

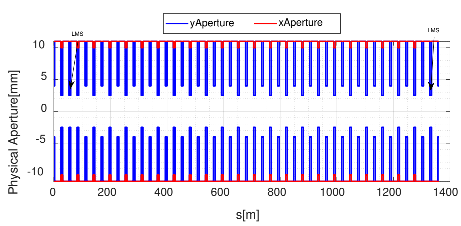

Figure 4: Schematic diagram of the physical aperture along the HEPS storage ring.

The beam, formally, is defined by a vector of 6*N values at a time t in the ELEGANT, each particle in the beam has six coordinates (x, p_x, y, p_y, z, p_z). We perform simulation of elastic scattering at multiple s locations and get the maximum of (p_x, p_y) that could be captured by the lattice, as shown in Figure 5, which is similar the dynamic aperture (x, y). The coordinates (p_x, p_y) is more suitable to describe the scattering process.

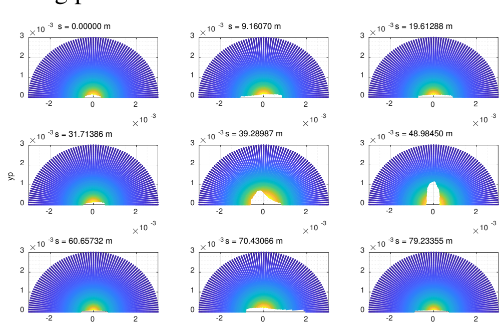

Figure 5: Scattering Angle distribution at different positions.

From the multi-particle tracking results, we could get the loss distribution as shown in Figure 6 and elastic gas scattering lifetime is 136 hours.

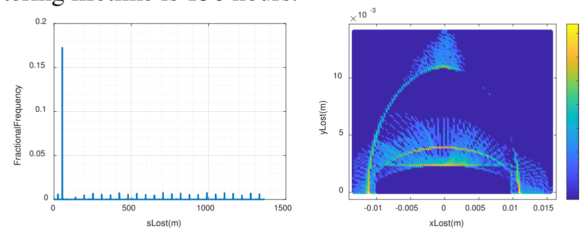

Figure 6: The histogram of particle loss distribution caused by elastic scattering and the transverse position of loss.

From Figure 6, most of the particles are lost in the first Lamberson section where the beta function is high and the vertical physical aperture is small.

BREMSSTRAHLUNG LIFETIME

Inelastic scattering (Bremsstrahlung) is an effect of deceleration and photon emission due to beam interaction with the residual gas atoms. The electron gets lost if its relative momentum deviation exceeds the limiting momentum half-aperture of the ring, this limiting momentum half aperture could be due to the RF bucket momentum half height or to physical or dynamical aperture considerations.

The lifetime due to bremsstrahlung is given by [5]:

$$\frac{1}{\tau_{bs}[s]} = \frac{4r_e^2 c N_A}{137R} L(\delta_{Acc}) \frac{1}{T[K]} \sum_{atom,j}\left[\ln\left(\frac{183}{Z_j^{1/3}}\right) Z_j \left(Z_j+\xi\right) \sum_{gas,j} \alpha_{ij} P_i [Pa]\right] \quad (2)$$

With

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

δ_{Acc} is the momentum acceptance and other variables are explained in section elastic scattering.

For a residual gas composition of 80% H_2 and 20% CO, the Bremsstrahlung lifetime of HEPS is about 250 hours for 1 *nTorr* pressure with local momentum acceptance as show in Figure 7.

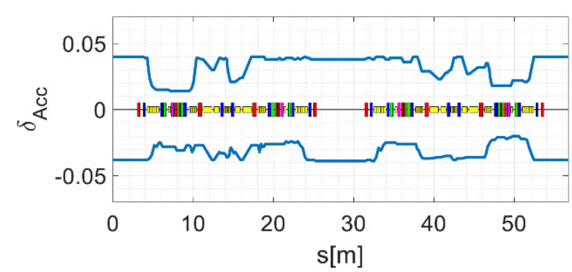

Figure 7: The momentum acceptance for the HEPS

Considering the magnetic field error and misalignment effect on the local momentum acceptance, 200 random error seeds were used for local momentum acceptance tracking with 4% RF energy acceptance as show in Figure 8 and the results of Bremsstrahlung lifetime are shown in Figure 9.

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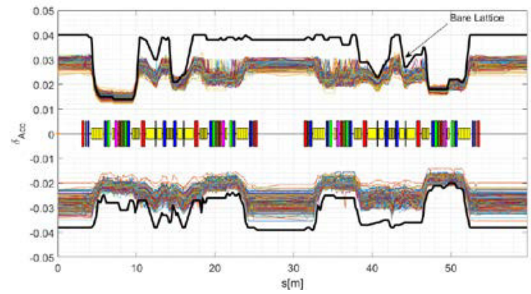

Figure 8: Local momentum acceptance of 200 random error seeds for HEPS.

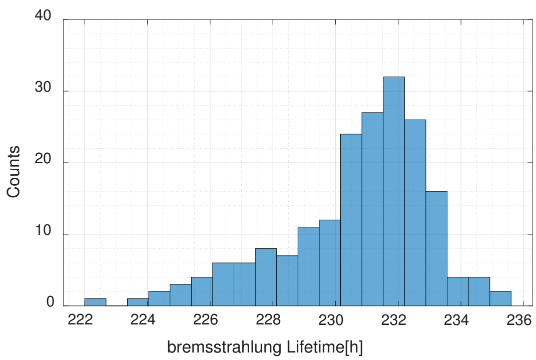

Figure 9: Bremsstrahlung lifetime distribution (200 random error seeds).

Take the tenth-lowest set as the reference standard, the Bremsstrahlung lifetime with error effects is about 180 hours.

Multi-particle tracking was done by ELEGANT on the condition that the initial beams have relatively large momentum deviation. We could get the beam loss distribution and the allowable maximum energy of the bremsstrahlung photon at multiple s locations as shown in Figure 10.

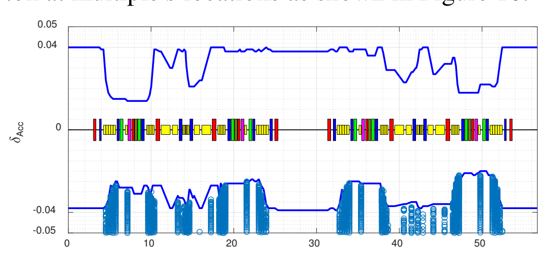

Figure 10: Allowable maximum energy of the bremsstrahlung photon at multiple locations.

By analysing the initial scattering location, initial scattering energy loss, and loss coordinates of the loss particles, the Bremsstrahlung lifetime is 258 hours for 1 *nTorr* pressure at the condition of the residual gas composition of 80% H_2 and 20% CO.

CONCLUSION

After the above analytical calculation and particle tracking simulation, consider the error effect and physical aperture limitation, under the condition of ideal vacuum 1 *nTorr*, the residual gas life is about 90 hours. During commissioning with the increase of the current intensity, the vacuum maybe worsen by an order of magnitude because of photon-stimulated desorption. As the insert devices increases, the local vacuum maybe worsen and the dynamic aperture decrease, the residual gas lifetime will be further reduced, more detailed analysis will be carried out.

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