ANALYTICAL ESTIMATION OF ATF BEAM HALO DISTRIBUTION *

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Abstract

Halo distribution is a key topic for background study. This paper has developed an analytical method to give an estimation of ATF beam halo distribution. The equilibrium particle distribution of the beam tail in the ATF damping ring is calculated analytically with different emittance and different vacuum degree. The analytical results agree the measurements very well. This is a general method which can be applied to any electron rings.

INTRODUCTION

The distribution function of an electron bunch, transverse or longitudinal, is often assumed to be Gaussian. Actually, however, due to stochastic processes, there always exists some deviation and hence charge distributions of accelerator beams can be separated into two parts: the beam cores, which usually have Gaussian-like distributions, and the beam halos, which have much broader distributions than the beam cores. The central part affects the luminosity of colliders, circular or linear, and the brightness of synchrotron light sources, while the halos can give rise to background in collision experiment detectors and even reduce the lifetime if its distribution is too large.

At the interaction point (IP) of ATF2 (Accelerator Test Facility 2), an elaborately designed beam size monitor based on laser interferometer technology, called the Shintake monitor, is utilized to measure the sub-100 nm electron beam size [1]. The photon background in the IP section will influence the modulation of the Shintake monitor, however, and hence degrade the resolution of beam size measurements. So the beam halo distribution is important for the measurement of the beam size at IP. Since beam halo scattering with the beam pipe is the main source of background, in order to study the charge distribution of the beam halo along the ATF2 beam line and develop a collimation strategy, we need to know the halo status at the entrance of ATF2 and furthermore how it is generated in the ATF damping ring. We have developed a set of theory to make an analytical estimation of halo distribution in ATF due to several common stochastic processes [2]. (Typical ATF damping ring parameters are listed in Table 1.) From reference [2], we know that the transverse halo distribution in ATF is dominated by beam-gas scattering effect. This paper will concentrate on beam-gas scattering with different beam emittance and vacuum level.

In order to measure the beam halo distribution and make comparison with analytical estimation, KEK-ATF2 developed a beam halo monitor which has both high resolution and high sensitivity based on fluorescence screen. A YAG: Ce screen, which has 1 mm slit in the center was set in the beam line. The image on fluorescence screen is observed by imaging lens system and CCD camera. In this configuration, the beam in the core will pass through the slit. The beam in surrounding halo will hit the fluorescence screen, and we can observe the distribution of beam halo. The intensity contrast of beam halo to the beam core is measured by scanning the beam position for the fixed fluorescence screen position. The detail of the beam halo monitor and the measurement results are in reference [3].

Table 1: Typical ATF Parameters

Parameter	**Value**
Energy E_0 (GeV)	1.3
Natural energy spread δ_0	5.44×10^{-4}
Energy acceptance	0.005
Average $\beta x/\beta y$ (m)	3.9/4.5
Horizontal emittance (nm)	1.3
Vertical emittance (pm)	20
Transverse damping time (ms)	18.2/29.2
Longitudinal damping time (ms)	20.9

THEORY OF BEAM-GAS SCATTERING

The performance of accelerators and storage rings depends on the many components of the accelerator, and one very important component is the vacuum system. Interactions between the accelerated particles and the residual gas atoms may degrade the beam quality. The lifetime may be reduced and/or the emittance may increase. The beam halo is possibly generated because the particles' distribution deviates from a Gaussian distribution.

The deflection of an electron via the Coulomb interaction is described by Rutherford scattering. We assume that this scattering is elastic and that the recoil momentum of the residual gas is negligible. The differential cross-section of the electron scattering with an atom is given by [4]

$$\frac{d\sigma}{d\Omega}=\left(\frac{2Zr_e}{\gamma}\right)^2\frac{1}{(\theta^2+\theta_{\min}^2)^2} \quad (1)$$

where Z is the atomic number, r_e is the classical electron radius, γ is the relativistic Lorentz factor and $\theta_{\min}$ is determined by the uncertainty principle as

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$$\theta_{\min} = \frac{Z^{1/3}\alpha}{\gamma} \tag{2}$$

where α is the fine structure constant. If we integrate over the whole space angle Ω, we obtain the total cross-section

$$\begin{aligned}\sigma_{tot} &= \int_0^{2\pi}\int_{\theta_{\min}}^{\pi}\left(\frac{2Zr_e}{\gamma}\right)^2 \frac{1}{\left(\theta^2+\theta_{\min}^2\right)^2}\sin\theta d\theta d\varphi \\ &\approx 4\pi Z^{4/3}(192r_e)^2\end{aligned} \tag{3}$$

We then need to get the probability density function $f(\theta)$. Assuming $\theta^2 = \theta_x^2 + \theta_y^2$, then integrating over one direction will give the differential cross-section for the other direction

$$\frac{d\sigma}{d\theta} = \frac{4\pi r_e^2 Z^2}{\gamma^2}\frac{1}{\left(\theta^2+\theta_{\min}^2\right)^{3/2}} \tag{4}$$

Here and hereafter we denote

$$\theta \equiv \theta_x(\theta_y) \tag{5}$$

Thus,

$$f(\theta) = \frac{1}{\sigma_{tot}}\frac{d\sigma}{d\theta} = \frac{\theta_{\min}^2}{\left(\theta^2+\theta_{\min}^2\right)^{3/2}} \quad \left(\int_0^\infty f(\theta)d\theta = 1\right) \tag{6}$$

For the elastic scattering, we assume that CO gas is dominant for beam-gas scattering in ATF, so that the total scattering probability in a unit time is

$$N = Q\sigma_{tot}c \tag{7}$$

where c is the speed of light and Q is the number of gas molecules in a unit volume, given by

$$Q = 2.65\times10^{20} nP \tag{8}$$

where n is the number of atoms in each gas molecule and P is the partial pressure of the gas in pascals. Here for ATF, Z=$50^{1/2}$ and n=2.

The collision probability of electron and gas atoms during one damping time is

$$N_\tau = N\tau \tag{9}$$

where τ is the transverse damping time for either the horizontal or vertical direction.

Finally, one gets the beam transverse distribution as

$$\begin{aligned}\rho(X) &= \frac{1}{\pi}\int_0^\infty \cos(kX)\exp[-\frac{k^2}{2}+\frac{2}{\pi}N_\tau\times \\ &\int_0^1 \frac{\left(\int_0^\infty \cos(\frac{k}{\sigma_0'}x\theta)f(\theta)d\theta\right)-1}{x}\arccos(x)dx]dk \\ &= \frac{1}{\pi}\int_0^\infty \cos(kX)\exp[-\frac{k^2}{2}+\frac{2}{\pi}N_\tau\times \\ &\int_0^1 \frac{\Theta xkK_1(\Theta xk)-1}{x}\arccos(x)dx]dk\end{aligned} \tag{10}$$

where Θ is the minimum scattering angle normalized by angular beam size, which is defined by $\frac{\theta_{\min}}{\sigma_0'}\left(\sigma_0' = \frac{\sigma_0}{\beta}\right)$, and X denotes both horizontal and vertical normalized coordinate. This formula tells us that the beam distribution disturbed by the beam-gas scattering effect is decided by only two parameters, the normalized scattering frequency N_τ and the minimum normalized scattering angle Θ.

ANALYTICAL RESULTS OF ATF BEAM HALO DISTRIBUTION

According to Eq. (10), we calculated the beam halo distribution with different emittance and different vacuum degree. The analytical results agree the measurements very well [3].

Halo Distribution with Different Vacuum Pressures

- E_0=1.3GeV, ε_x=1.3nm, ε_y=20pm

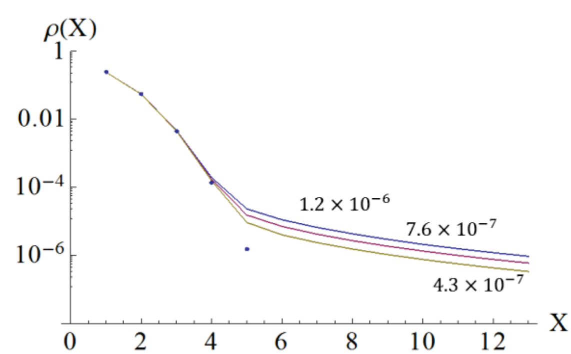

Figure 1: Horizontal beam distribution with different vacuum pressures (horizontal coordinate X is normalized by RMS beam size).

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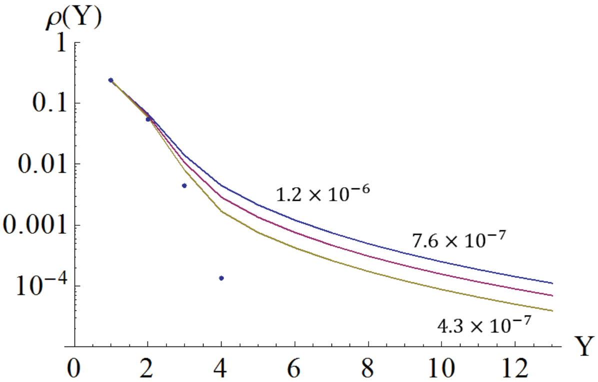

Figure 2: Vertical beam distribution with different vacuum pressures (vertical coordinate Y is normalized by RMS beam size).

From Fig. 1 and Fig. 2, we can see that due to the beam-gas scattering effect, the beam distribution will deviate from a Gaussian distribution. Worse vacuum status will give a larger beam halo and smaller Gaussian beam core. Also, it can be seen that the vertical distribution of a beam is affected more than the horizontal distribution by the elastic beam-gas scattering because $\sigma_{y0}' << \sigma_{x0}'$, so $\Theta_y >> \Theta_x$.

Halo Distribution with Different Emittance

- E_0=1.3GeV, P= 10^{-6} Pa

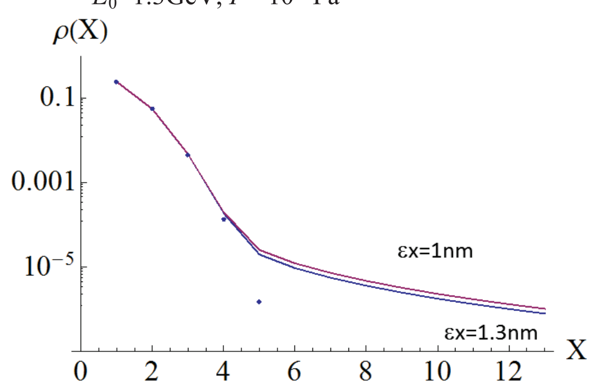

Figure 3: Horizontal beam distribution with different emittance (horizontal coordinate X is normalized by RMS beam size).

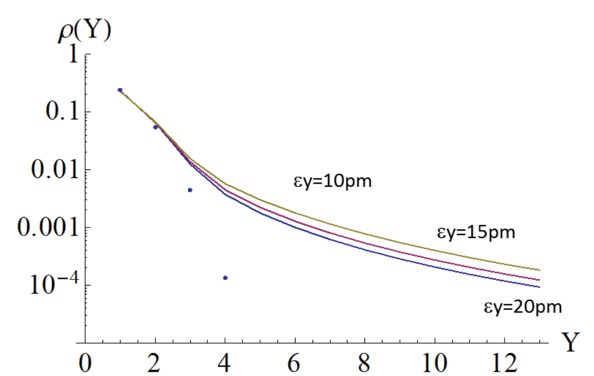

Figure 4: Vertical beam distribution with different emittance (vertical coordinate Y is normalized by RMS beam size).

Figures 3 and 4 show that larger emittance will give smaller halo.

CONCLUSION

Due to various incoherent stochastic processes in the electron (positron) rings in an accelerator, the beam distribution will deviate from a Gaussian shape, generating a longer beam tail and increasing the beam dimensions. With the background issue, we have to study the halo distributions and the mechanisms by which the halo particles are produced. Take ATF as an example, we try to estimate the halo status with different emittance and vacuum level. In this paper, we have calculated the whole beam distribution of the ATF damping ring, including the halo section, looking at beam-gas scattering effect, based on the existing theory in reference [2]. By comparing with measurements, we saw a good agreement between the analytical method and the experimental results. The analytical method developed in this paper is not specific to ATF and can be utilized on any other electron ring.

For the RMS emittance growth, we do have some mature theories and numerical codes to use, while for the whole beam distribution, especially for the halo part, there are few mature theories. Even using simulations, it's still difficult to get the halo distribution for three directions because the beam halo includes much fewer particles than the beam core. For the first time, we have analyzed the whole beam distribution of the ATF damping ring, including the halo section, with different emittance and vacuum level. From our study, we know that the transverse halo in ATF is dominated by beam gas scattering, and also smaller emittance and worse vacuum give larger beam halo.

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