TRANSVERSE ACCEPTANCE STUDIES AT THE ATF DAMPING RING*

F. Zimmermann, M.G. Minty, J.L. Turner, M.D. Woodley, SLAC, Stanford, USA,
J. Urakawa, H. Hayano, K. Kubo, T. Mimashi, N. Terunuma, N. Toge, KEK, Tsukuba, Japan,
T. Okugi, Tokyo Metropolitan University, Tokyo, Japan

Abstract

The transverse acceptance of the ATF damping ring, estimated from the beam current decay and the time-dependent vacuum pressure, is smaller than the design value. We have measured its dependence on sextupole settings, linear coupling, global orbit distortions, local orbit bumps, rf frequency, rf voltage, and on the working point in the tune diagram. We describe the procedure applied to infer the acceptance, present the measurement results and compare them with simulations.

1 INTRODUCTION

The ATF damping ring is a prototype damping ring designed to develop the technologies and operational procedures required for a next-generation linear collider. Most of the measurements reported in this paper were performed for a beam energy of 1.265 GeV and a relaxed optics with 90° phase advance per cell (measurements for the design lattice with 135° phase advance per cell gave similar results). Other beam and machine parameters were: equilibrium emittance $\epsilon_x \approx 2$ nm, revolution frequency 2.16 MHz, rf voltage 280-400 kV, (harmonic number 330,) energy loss per turn 40 keV, transverse damping times $\tau_{x,y} \approx 13, 30$ ms, rms momentum spread 8×10^{-4}.

In spring 1998, the beam lifetime in the ATF was limited almost entirely by elastic scattering off residual-gas molecules [1]. In the future, for higher charge, smaller vertical emittance, and decreasing vacuum pressure, the Touschek (intra-beam) scattering is also expected to become important. Including both of these effects, the current decay of the stored beam is described by the equation

$$\frac{1}{N(t)}\frac{dN(t)}{dt} = -\alpha p(t) - \beta N(t) \qquad (1)$$

where $p(t)$ is the average residual-gas pressure, N the bunch population and t the time. The first term on the right-hand side represents the gas scattering, the second term the Touschek effect. Figure 1 (left) shows a typical decay of the beam current during a store. The figure illustrates that the average pressure decreases with decreasing beam current. Integration of Eq. (1) yields

$$1-n(t) = \alpha \int_0^t p(t')\, n(t')dt' + \beta N_0 \int_0^t n(t')^2 dt' \quad (2)$$

where $n(t) \equiv N(t)/N_0$ denotes the normalized bunch population with $N_0 = N(0)$. The two integrals on

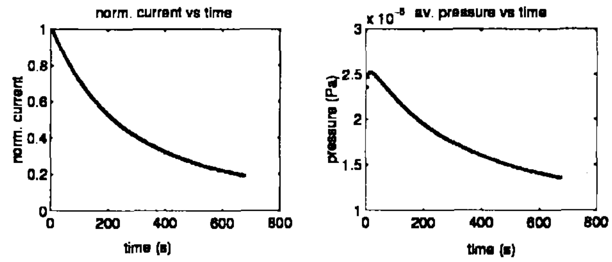

Figure 1: Left: current (dimensionless) vs. time; right: average pressure vs. time.

the right-hand side are easily evaluated as a function of time, using current data from a DCCT (dc current transformer) to determine $N(t)$, and the readings of 30 pressure gauges, sampled about once per second, to infer the average pressure. The coefficient α is given by [1]

$$\alpha \left[\frac{1}{\mathrm{Pa\,s}}\right] \approx \frac{7.2\times 10^{28}}{\mathrm{Pa\,s\,m^2}}\;\frac{2\pi r_0^2 \sum_i Z_i^2}{\gamma^2}\;\frac{<\beta>}{A} \qquad (3)$$

where the sum extends over the constituent atoms of the residual-gas molecules, γ is the relativistic Lorentz factor for the beam, $<\beta> = <\beta_{x,y}> \approx 2.5$ m is the average beta function in the arcs, and A the radial acceptance of the ring (the value of $<\beta>/A$ is assumed to be the same in both transverse directions[1]). The acceptance A represents either a physical or a dynamic limit (due to nonlinearities), whichever is smaller. If the effect of Touschek scattering is small, we can plot the normalized current n as a function of the integral $\int p(t')n(t')\,dt'$. As shown in Fig. 2, this results in a straight line, whose slope is inversely proportional to the acceptance A. The small departure from linearity for large beam current is due to the Touschek effect.

A fit of $n(t)$ as a linear function of the two integrals $\int p(t')n(t')\,dt'$ and $N_0 \int n(t')^2\,dt'$ yields α and β of Eq. (2). Using Eq. (3) and assuming nitrogen (N_2) or carbon monoxide (CO) molecules as the main constituents of the residual gas, we can calculate the acceptance $A \approx 1.4 \times 10^{-4}\; 1/\alpha$ m/(Pa s). The Touschek lifetime for the bunch population N_0 (*e.g.*, $N_0 = 10^{10}$) is simply τ_{Tou} [s] $= 1/\beta[\mathrm{s}^{-1}]$. From the fitted value τ_{Tou}, the vertical beam emittance can be determined [2]. However, in the following we assume $\beta = 0$ and thereby ignore the small Touschek contribution to the lifetime.

* Work supported by the U.S. Department of Energy under contract DE-AC03-76SF00515.

[1] If the acceptance is only limited in one plane of motion, for example vertically, Eq. (3) still applies if we replace $<\beta>/A$ by $<\beta_y>/(2A_y)$.

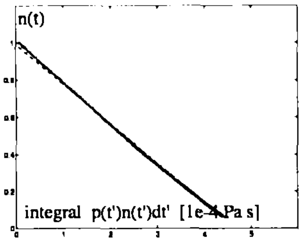

Figure 2: Normalized bunch population vs. integral $\int p(t')n(t')\, dt'$ (in Pa s): dotted – measurement; dash-dotted – prediction of fit to the integral ($\int p(t')n(t')\, dt'$).

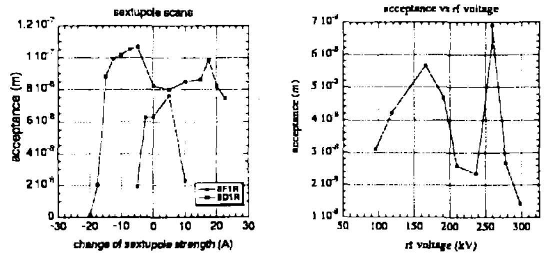

Figure 4: Left: measured acceptance vs. the strength of the two main sextupole families, varied separately. Right: acceptance vs. the amplitude of rf voltage; nominal rf voltage at the time of measurement was 270 kV.

2 MEASUREMENTS

All measurements yield an acceptance value of about 10^{-7} m ^{2}, a factor 50 smaller than expected (see Section 3). The measured acceptance corresponds to a 1 mm half aperture at a location with 10 m beta function. The design physical aperture is much larger than this: The half aperture is 12 mm in the arcs, 5 mm at a photon mask in the wiggler section, 6 mm at a mask in the South straight section, and 7 mm at the septum [3, 1]. The smallest half aperture is 3.5 mm, in the extraction kicker chamber, with a nominal beta function of about 6 m, and a corresponding acceptance of 2×10^{-6} m, assuming the model optics; note that the measured beta functions are fairly consistent with the model [4].

In Fig. 3, the measured acceptance is shown vs. the excitation of 4 orthogonal steering magnets. For each steering magnet, the available aperture was about ±1 mm (maximum orbit change in the arcs), corresponding to a current change of ±2 A. This aperture limit is consistent with the beam lifetime measured for a centered orbit. The vertical scans (left figure) exhibit a flat plateau at the center of the scan, while the horizontal scans (right figure) are peaked, suggesting that the aperture is tighter in the horizontal plane. Excitation of skew quadrupoles had no noticable effect on the beam lifetime.

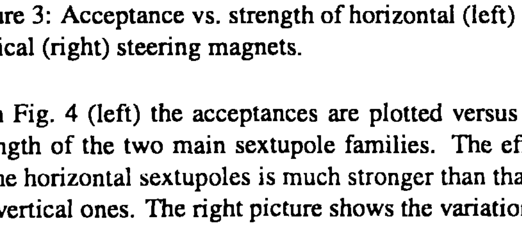

Figure 3: Acceptance vs. strength of horizontal (left) and vertical (right) steering magnets.

In Fig. 4 (left) the acceptances are plotted versus the strength of the two main sextupole families. The effect of the horizontal sextupoles is much stronger than that of the vertical ones. The right picture shows the variation of the acceptance as a function of the rf voltage which was observed in March 1998. The nominal voltage was 270 kV, near the maximum acceptance value. The sharp decrease in acceptance for voltages both higher and lower than the nominal value is not understood. Measurements in May 1998 did not reproduce this strong sensitivity. It might have reflected the location of synchrobetatron resonances, or it could have pointed to a problem with the rf system. The decline in beam lifetime for very low rf voltages is probably due to Touschek scattering (the Touschek effect scales roughly as $\sqrt{V_{rf}}$).

We also performed lifetime scans in the tune plane. Figure 5 (left) presents the variation of the horizontal and vertical tunes vs. the strength of the main quadrupole family QF2R. The right picture shows the corresponding acceptance. The beam could not be stored below a horizontal tune of about 0.15, indicating a wide stop band at the integer resonance. Clearly visible are also the third and half integer resonances. If the third integer resonance is driven by a single sextupole of strength k_s, in the vicinity of this resonance the acceptance should be a quadratic function of $\Delta Q_3 = (Q - 1/3)$, namely $A \approx (24\pi\ \Delta Q_3/(k_s\beta^{3/2}))^2$, where β is the beta function at the sextupole. Similarily, if an octupole of strength k_o drives the half integer resonance, the acceptance near the resonance should be a linear function of $\Delta Q_2 = (Q - 1/2)$: $A \approx 24\pi\ |\Delta Q_2|/(k_o\beta^2)$. The measurements near $Q \approx 1/3$ are fitted by $A \approx 3 \times 10^{-4}$ [m] $(\Delta Q_3)^2$ and those near $Q \approx 1/2$ by $A \approx 2 \times 10^{-6}$ [m] $|\Delta Q_2|$. Assuming $\beta \approx 5$ m, a bore radius of 12 mm, and a length of 1 m, this translates into a pole tip field of 1 kG for the sextupole and 18 kG for the octupole component.

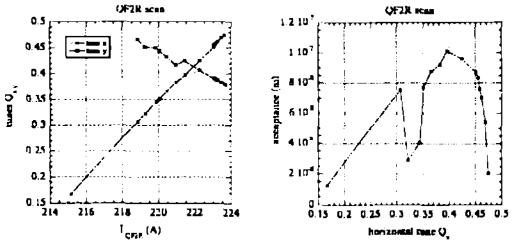

Figure 5: Left: variation of the horizontal and vertical tune as a function of quadrupole-string excitation. Right: transverse acceptance plotted vs. the horizontal tune.

[2]Recent measurements give a slightly improved value of 2×10^{-7} m.

For induced oscillations up to 1–2 mm in amplitude we could not detect any amplitude-dependent tune shift. At stronger excitation we occasionally observed a smaller or even vanishing tune signal without any beam loss, which could indicate a very fast decoherence.

From first-turn beam loss induced by various global and local orbit changes [5, 6], a physical acceptance of 2–10 $\times 10^{-6}$ m-rad was deduced [6], in good agreement with the known aperture restrictions.

3 SIMULATIONS

Tracking simulation studies with MAD [7] predict an acceptance between 5×10^{-6} and 10^{-5} m-rad, for both the 90° and the 135° optics. This is a factor of 50–100 larger than the measured acceptance. The simulations show that synchrotron oscillations have only a marginal effect on the acceptance, that an increase in the number of turns tracked from 1000 to 5000 (the horizontal damping time corresponds to about 3–4×10^4 turns) results in an acceptance reduction of about 20% (10% reduction in aperture), and that random quadrupole gradient errors of 1% rms reduce the acceptance by a similar amount. The effect of multipole errors in the bending magnets was simulated, rather arbitrarily assuming the same random and systematic multipole components as specified for PEP-II [8], but scaled to the smaller gap size of the ATF magnets (32 mm bending-magnet full gap instead of 71 mm in the PEP-II HER). Even for 10 times larger multipole coefficients b_n ($n = 2, \ldots, 6$), the dynamic acceptance was reduced by not more than 20%, far too little to explain the observed discrepancy. Finally, quadrupole rms misalignments of 200–300 μm could reduce the acceptance to 2×10^{-6} m [3], still 20 times larger than measured.

Figure 6 (left) shows the simulated effect of a closed orbit distortion. It should be compared with the measurement of Fig. 3. The variation with the corrector strength is similar (in the simulation the same relative decrease of the acceptance occurs for about a factor 2 larger corrector change), but the vertical scale is different by almost two orders of magnitude. In the simulation, changing the SF and SD sextupole strengths has about the same effect on the acceptance, in contrast to the observed large difference in sensitivity.

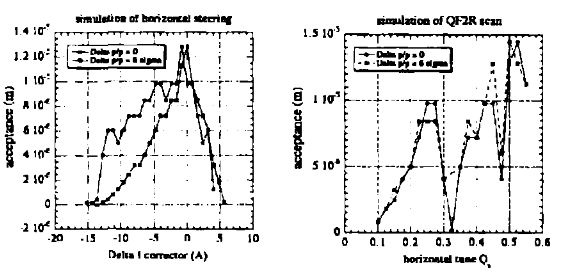

Figure 6: Left: simulated acceptance vs. the strength of a horizontal steering magnet. Right: simulated acceptance vs. the horizontal tune.

The simulated stop-band widths around the 1/3 and 1/2 integer resonances, shown in Fig. 6 (right), are comparable in size to the measured widths of Fig. 5, but also in this case the vertical scale is quite different.

4 CONCLUSION

Simultaneous measurements of beam current decay and vacuum pressure permit an easy evaluation of the ATF transverse acceptance. The measured acceptance is 1–2 orders of magnitude smaller than the design physical and dynamic acceptances (a factor 7 smaller in aperture). It depends strongly on the strength of the horizontal sextupoles, and, to some extent, on the working point in tune diagram, but it is fairly independent of vertical sextupoles and skew-quadrupole settings. In February and March 1998, the acceptance was also extremely sensitive to the rf voltage. The lifetime reduction observed with an orthogonal set of closed-orbit distortions shows an aperture limit in both betatron phases at a 1-mm amplitude, roughly consistent with the beam lifetime. The aperture restriction in the horizontal plane appears to be tighter than that in the vertical. The measured acceptance reduction near the 1/3 and 1/2 integer resonances points to the presence of a large nonlinear field.

We conclude that an extremely small dynamic aperture is the most probable explanation for the short beam lifetime. In the future, we intend to reconstruct the nonlinear Hamiltonian governing the beam motion in the ATF damping ring from multi-turn orbit data [9, 10].

5 ACKNOWLEDGEMENT

The authors acknowledge support by K. Takata and M. Ross. F. Zimmermann, M. Minty, J. Turner and M. Woodley thank the KEK ATF group for extraordinary hospitality. This work was supported in parts by the US Department of Energy under the contract no. DE–AC03–76SF00515.

6 REFERENCES

[1] C. Montag, *et al.*, ATF 97-18 (1997).

[2] T. Okugi, *et al.*, presented at EPAC98, SLAC-PUB-7859 and ATF 98-15 (1998).

[3] F. Hinode *et al.*, "Accelerator Test Facility—Design and Study Report", KEK Internal Report 95-4 (1995).

[4] J. Potier *et al.*, presented at APAC 98, SLAC-PUB-7784 and ATF 98-07 (1998).

[5] F. Zimmermann, *et al.*, SLAC/AAS-94 and ATF 98-10 (1998).

[6] M. Minty, M. Woodley, ATF 98-11 (1998).

[7] H. Grote and C. Iselin, CERN Report No. CERN/SL/90-13 (1990).

[8] "PEP-II. An Asymmetric B Factory", SLAC-418, LBL-PUB-5379 (1993).

[9] R. Bartolini and F. Schmidt, "Normal Form via Tracking or Beam Data", Part. Accelerators (in press) and LHC Project Report 132 (1997).

[10] C.-X. Wang and J. Irwin, SLAC-PUB-7547 (1997).