Beam-Intensity Measurement with a DC Current Transformer at the Photon Factory Storage Ring

Tohru Honda, Yoshihiro Sato and Tomotaro Katsura
Photon Factory, National Laboratory for High Energy Physics
Oho 1-1, Tsukuba, Ibaraki 305, Japan

Abstract

A new system for measuring the stored beam currents was built using a DC current transformer (DCCT). A sufficient resolution of 2 μA was accomplished for the current measurement under multi-bunch operation. A magnetic shield against stray fields in the ring tunnel successfully suppressed zero drifts within 12 μA. Under single-bunch operation, a heating-up problem of the sensor toroid took place. The resolution and stability of the measurement were inferior to those under multi-bunch operation. This degradation was attributed to thermal strains induced in the sensor cores.

I. INTRODUCTION

The Photon Factory storage ring (PF ring) is a synchrotron-radiation source operated with 2.5-GeV positron beams. The PF ring is characterized by the long life of its stored beam. At present, the product of the current and lifetime ($I_b \cdot \tau$) exceeds 1000 Amin under multi-bunch operation [1]. The initial stored current is usually 360 mA. The stored current decreases to about 250 mA at the end of 24-hour operation, and the beam lifetime amounts to 70 hours. This lifetime corresponds to a beam loss of just 1 μA in one second. The stored lifetime is continuously recorded every 10 seconds in order to monitor the operational condition of the accelerator. A resolution and stability of better than a few micro-amperes is required for the current measurement. In order to realize the specific resolution, we built a new system for measuring the current using a DCCT. The DCCT unit was Parametric Current Transformer [2] manufactured by BERGOZ Co., France.

In the present paper, we report on the installation of the DCCT toroid and our experience in measuring beam currents at the PF ring.

II. INSTALLATION OF DCCT

A. Vacuum Chamber

A cross-sectional view of the vacuum chamber for the DCCT sensor is shown in figure 1. The DCCT was installed downstream of a long straight section. The beam duct was made of stainless steel having a circular cross section. A ceramic ring of 25 mm in length insulated the wall current flowing inside the DCCT toroid. A water-cooled copper cylinder protected the toroid from heating-up during a bake-out of the vacuum duct. For the bake-out procedure, tape heaters and thermal insulators (not shown in the figure 1) were placed between the vacuum duct and the copper cylinder. The temperature of the toroid was held under 45 °C while the duct was baked out at about 180 °C. Four stainless-steel rods maintained the mechanical rigidity of the chamber. An external bypass for the wall current comprised four rods and a copper shield enclosing the entire assembly.

B. Magnetic Shielding

The operation energy of the PF ring ranges from 0.75 to 3 GeV during the time of accelerator-physics studies [1]. Acceleration and deceleration of a stored beam are accompanied by variations of stray fields from bending and quadrupole magnets. The background field near to the DCCT assembly reaches about 25 G under 3-GeV operation. The DCCT has a high sensitivity of 100 μA/G to the radial magnetic field [3]. The zero drift due to a stray field would amount to 2 mA without any magnetic shields.

Two concentric cylinders were applied in order to reduce the external field affecting the DCCT toroid. The outer cylinder was made of a permalloy which had a high-saturation flux density of $B_s \sim 1.5 \times 10^4$ G. The magnetic permeability of the permalloy was greater than 3×10^3, and the thickness was 1.2 mm. This material can act as an effective shield, even in a high field as large as several tens of gausses. The inner cylinder was made of a typical shielding material similar to a Mu-metal ($B_s \sim 0.7 \times 10^4$ G, $\mu > 3 \times 10^4$ and 2 mm in thickness). The transverse shielding factor of a long cylinder is written as

$$S_{\mathrm{i}} = \frac{\mu_{\mathrm{i}} t_{\mathrm{i}}}{2R_{\mathrm{i}}}, \qquad (1)$$

where μ_{i} is the magnetic permeability, t_{i} the thickness of the material and R_{i} the cylinder radius. In the case of a finite length cylinder, the factor reduces in the vicinity of both ends of the cylinder. The transverse shielding factor of a two-layer

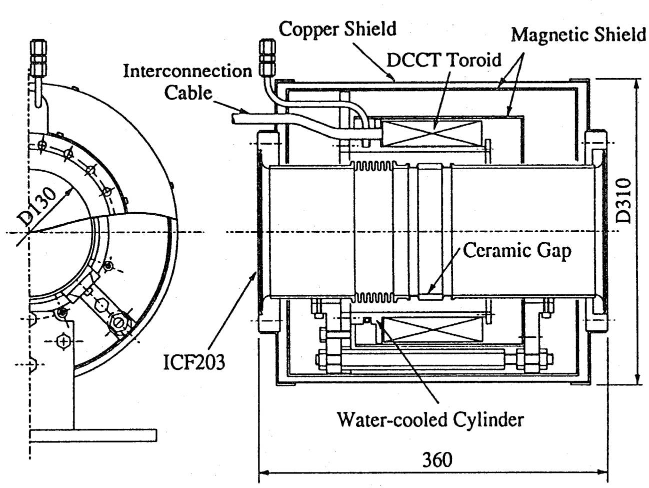

Figure 1. Mechanical design of the DCCT assembly.

arrangement is approximated by [4],

$$S = S_1 S_2 \left[1 - \left(\frac{R_1}{R_2}\right)^2 \right] , \qquad (2)$$

where subscripts 1 and 2 refer to the inner and outer shields, respectively. R_1 was determined at 120 mm to be as small as possible, since the shielding factor was inversely proportional to its radius. If the outer cylinder could be taken sufficiently long, equation (2) shows that the shielding factor assumes a maximum when the ratio R_2/R_1 equals $\sqrt{3}$, or R_2 is 210 mm. In the present case, the available length for the shield was limited to within 300 mm. Because the reduction in the length-to-radius ratio decreases the effective shield factor due to the end-effect, R_2 was determined as 145 mm to keep the length-to-radius ratio at about 2. As a result of the shielding, the magnetic zero drift of the DCCT was suppressed to within 12 μA, even at maximum exciting currents of the bending and quadrupole magnets. Steady current measurements were made possible without any zero adjustment of the DCCT, even when the operation energy was varied. The effective shielding factor for the transverse field could be estimated as $2\text{x}10^2$.

III. MEASUREMENT AND DISCUSSION

A. Data Acquisition

The associated electronic circuits with the toroidal sensor were placed in the machine room under the ring tunnel. The front-end electronics box was connected to the toroid by a 3-m long cable. A precision digital voltmeter (HP 3458A) was mounted on the same rack as the back-end control box. The transmission lines for the small voltage signals were kept as short as possible in order to minimize electrical interferences. In ordinary current measurements, the low-pass filtered output was fed into the voltmeter with an integration time of 20 ms. The full-scale range was fixed at ±1 A. The analog-to-digital converted signals were transmitted to the main control room via an extended GPIB bus. The full-bandwidth output (dc to 30 kHz) was used for measurements of fast current variations during accelerator-physics studies. The temperature of the DCCT toroid was continuously monitored by using a thermometer fabricated from optical fibers.

B. Resolution and Stability of the Measurement

Figure 2 is a record of the stored beam current and its lifetime during 24 hours under multi-bunch operation. The beam current was measured at an interval of 10 seconds. The lifetime of the stored beam was calculated every 10 seconds based on a current variation sampled during the previous 1 minute. The lifetime (τ) was deduced by fitting an exponential curve, $I_b\exp(-t/\tau)$, to the sampled current data. The resolution of the current measurement was determined as a standard deviation of the sampled data from the evaluated curve. Under multi-bunch operation, the resolution with the 20-ms integration was 2 μA. The value was almost sufficient for the present procedure of current monitoring in the PF ring. Figure 3 shows a part of the beam stacking process measured during an injection period with a 4-ms integration time for the voltmeter. The resolution was so good that each stacking step of about 20 μA could be clearly resolved at an injection rate of 25 Hz.

One of the major factors that impairs the measurement stability is a temperature-dependent zero drift. Figure 4 shows the zero drift measured while the toroid was cooling down. A temperature coefficient of 8 μA/°C was deduced. The variation in the toroid temperature under multi-bunch operation was less than 4 °C. The zero drift due to the temperature variation was limited to about 30 μA. A long-term zero drift was confirmed to be within 10 μA after continuous operation of two months.

C. Heating-up Problem under Single-Bunch Operation

The PF ring is operated with a single-bunch beam during 10% of the user-time. The bunch length ranges from 50 ps to 100 ps, as dependent on the beam current [5], and the revolution frequency is 1.6 MHz. Figure 5 is a record of the current and the toroid temperature during a 12-hour single-bunch operation. The initial stored current was 50 mA, and the value of $I_b \cdot \tau$, was about 40 Amin. In contrast with the multi-bunch beam, the single-bunch beam caused a heating-up of the toroid. The temperature reached about 70 °C with a three-hour delay from the injection when no cooling was done. The zero drift amounted to about 0.4 mA when the temperature was varied from 25 to 70 °C.

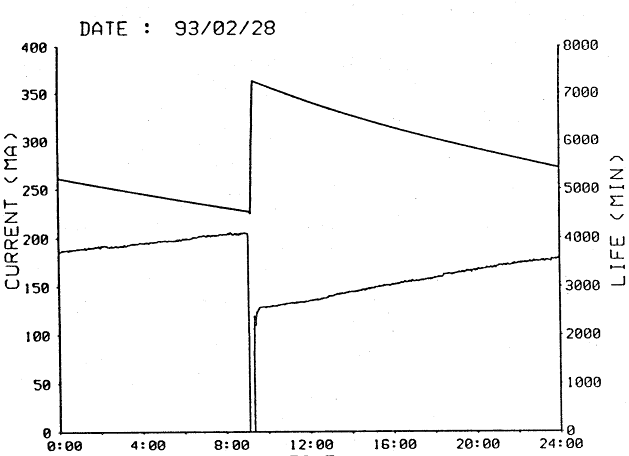

Figure 2. Beam current and lifetime during 24-hour multi-bunch operation.

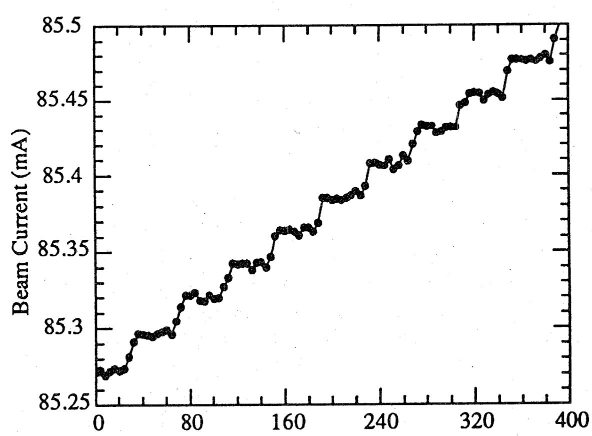

Figure 3. Beam stacking process during an injection period.

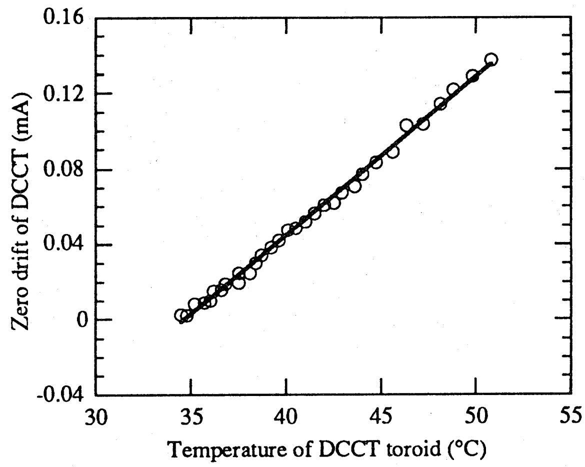

Figure 4. Temperature-dependent zero drift of the DCCT.

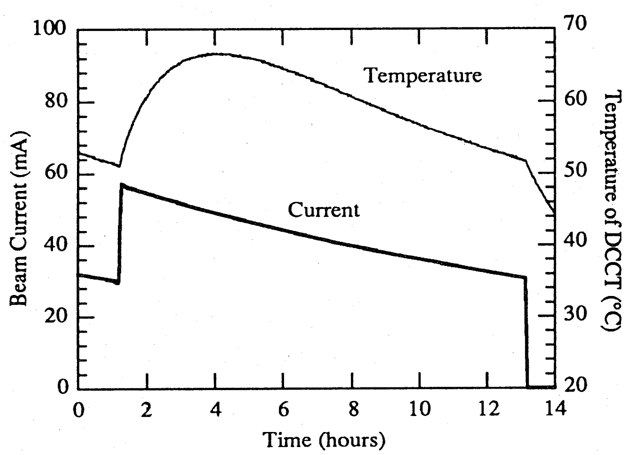

Figure 5. Beam current and temperature of the DCCT during 12-hour single-bunch operation.

Under single-bunch operation, the resolution of the current measurement was inferior to that under multi-bunch operation. The resolution was 5 μA, even while the toroid temperature was slowly decreasing. While the temperature was rapidly increasing after injection, the resolution degraded further. The temperature of the DCCT could be held below 50 °C by water-cooling of the copper cylinder, which was in contact with the inner surface of the toroid. However, it was found that the water-cooling gave rise to a large fluctuation in the current measurement. A typical fluctuation observed during five minutes is shown in figure 6. This measurement was made with an integration time of 1 s for the voltmeter. For example, an imaginary increase of the beam current by about 20 μA appeared at around 250 s. Such fluctuations of the order of several tens of μA were frequently observed. The characteristic time of the fluctuation was so long that ordinary low-pass filters could not eliminate the fluctuation. The degradation of the resolution observed just after injection was caused by a similar fluctuation.

The characteristic frequency of the fluctuation ranged far below that of electrical interferences and mechanical vibrations around the storage ring. The fluctuation of the current measurement was large when the temperature changed rapidly. Furthermore, the easy water-cooling caused a larger fluctuation. The cooling would produce a temperature gradient in the DCCT cores. The origin of the fluctuation was supposed to be attributable to unstable thermal strains induced in the magnetic modulator cores. The central part of the DCCT is the magnetic modulator comprising two cores, a small difference in the magnetic fluxes between the two cores generates a second-harmonic signal detected as the beam intensity. When the toroid temperature changes, the strict balance of the two cores is lost due to the uneven mechanical constraints in the two cores. This is the origin of the temperature-dependent zero drift of the DCCT [2]. In a similar way, variations of thermal strains in the cores would be detected as a fluctuation of the current measurement. The heating-up of the DCCT must be suppressed for an improvement in the resolution under single-bunch operation. The capacity of the insulation gap was measured to be about 40 pF. Increasing the capacity is expected to be effective for lowering the parasitic mode loss or the heating-up of the assembly.

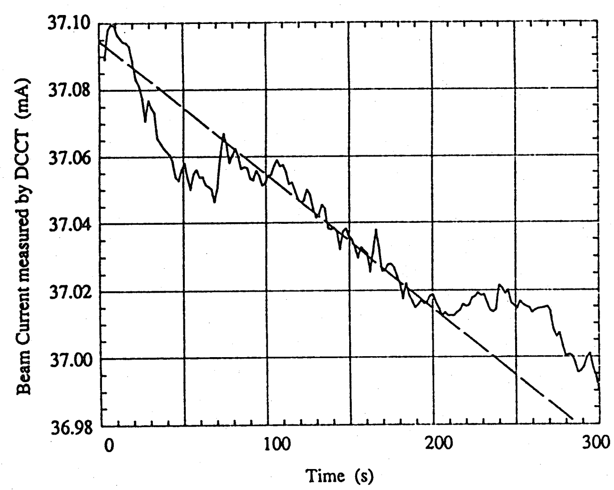

Figure 6. Typical fluctuation in the DCCT signal observed under single-bunch operation. The broken line is the speculated current with a constant beam-loss rate.

Acknowledgments

The authors would like to thank Dr. Y. Hori and Mr. Y. Takiyama for their support in the design and installation of the vacuum chamber. We also acknowledge other staff members of the Light Source Division for their support and useful discussions.

IV. REFERENCES

[1] Photon Factory Activity Report #10, "Summary of storage ring operation", R-2, 1992.
[2] K.B.Unser, " The parametric current transformer, a beam current monitor developed for LEP ",CERN SL/91-42.
[3] Catalogue of the "Parametric Current Transformer", BERGOZ, 01170 Crozet, France.
[4] T.J.Sumner, J.M.Pendlebury, and K.F.Smith, J.Phys.D, 20(1987)1095.
[5] N. Nakamura, S. Sakanaka, K. Haga, M. Izawa, and T. Katsura, Conference Record of the 1991 IEEE Particle Accelerator Conference, Vol. 1, p440.