Improvement of a Clipping Circuit in the BPM Readout Electronics for the ATF Damping Ring

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Abstract

The ATF damping ring has been operated since January in 1997 at KEK, and several beam studies have been started. For the orbit measurement, button-type beam position monitors (BPM) are installed in the ATF damping ring together with a conventional readout electronics. This readout electronics includes clipping circuits with Schottky diodes to measure a charge induced in each button-type electrode of a BPM by a beam. But Schottky diodes can hardly respond to high frequency components in a BPM signal. This fact finally limits the position resolution of BPM. However, the high position resolution will be increasingly required. Hence we tried to use an FET as a clipping device instead of a Schottky diode, and found out a few good properties to improve performance of the clipping circuit.

1 Introduction

The accelerator test facility (ATF) [1] was constructed in order to research and to develop necessary technology for future linear colliders. It consists of a 1.54-GeV injector linac, a damping ring, a beam transport line from the linac to the ring, and an extraction line for the beam diagnostics and several beam studies. We have started to operate the ATF damping ring since January in 1997.

To achieve as low an emittance as possible is one of critical issues to obtain a high luminosity in future linear colliders, as well as to achieve a high acceleration efficiency and a strong final focus. Future linear colliders require a very low vertical emittance, typically $\gamma\varepsilon_Y$ = 30 nm. A damping ring is the most feasible method for obtaining such a low emittance. The ATF damping ring has a race-track shape, and consists of 36 normal cells with a combined-function bending magnet and eight wiggler magnets to reduce the damping time. Normal cells form two arc sections, and wiggler magnets are put in two straight sections. The circumference is 138.6 m.

In order to achieve an extremely low emittance, we must correct the dispersion of the orbit, which is small (η < 2 mm) in the long wiggler section of the ATF damping ring. A precise measurement of the dispersion is indispensable. We usually obtain the actual dispersion by comparing each closed-orbit distortion under the conditions of different RF frequency ($\Delta f \approx$ 10 kHz). For this reason, the resolution of the beam position monitor (BPM) must be better than 5 µm.

2 BPM Readout Electronics

There are 96 button-type BPMs in the ATF damping ring. Most of BPMs have a cylindrical shape of inner diameter of 24 mm, and have four button-type pickup electrodes of 12 mm in diameter. BPM signals induced by a beam are sent to clipping modules through long cables (RG223/U), typically 40 m in length. Each cable length is determined by taking account of time of flight so as to detect BPM signals in a same turn by a common trigger signal synchronized with the beam revolution. Bipolar BPM signals are clipped in the clipping modules. Then unipolar output signals are integrated and digitized in a 14-bit charge-sensitive ADC. A gate signal for each ADC is generated from the common trigger signal. This BPM readout system allows us to measure the beam orbit in any turn with only one passage of the beam by changing delay time of the common trigger signal [2].

We have investigated signals of a button-type BPM induced by a beam with a bunch length of 20 ps (6 mm) in the ATF linac by using a digital sampling oscilloscope Tektronix 11802 with a 20-GHz sampling head SD-24. BPM signals passing through a 33-m cable have a negative swing with a pulse width of 200 ps in FWHM followed by a longer positive tail. BPM signals have main frequency components around a few GHz. Thus the clipping module is required to operate at as high a frequency as possible.

3 Tests of Clipping Circuits

In general, a diode is used to clip a bipolar pulse. But a *pn*-junction diode can not respond to fast pulses because of storage of minority carriers. The *pn* junction under the forward bias stores minority carriers diffused across the junction and not recombined with a major carrier. When the bias is reversed, these minority carriers diffuse in the reverse direction. Whereas a Schottky diode which has a metal-semiconductor junction has no storage of minority carriers. Therefore, we used Schottky diodes in the clipping module. Nevertheless, the clipping module needs a low-pass filter of 30 MHz for keeping the operation stable. In addition, the clipping module needs amplification of a signal passing through a low-pass filter, because a frequency component of 30 MHz in a BPM signal is minor. If a clipping circuit which can operate at a higher frequency is available, the position resolution of BPM will be improved together with the S/N ratio. Furthermore, the production cost of clipping modules will be able to be reduced, because number of parts will be reduced.

In this paper, we study the performance of another clipping device. We tried to make use of a junction field-effect transistor (FET) under the class B operation. A bipolar junction transistor was not tried because of the same reason as a *pn*-junction diode.

3.1 Clipping Circuit using Schottky Diode

The essential part of the clipping module is investigated to compare with an FET clipping circuit. The current-voltage characteristic of a Schottky diode can be written as

$$I = I_0\{ e^{\frac{eV}{k_B T}} - 1 \},$$

where I_0 is the saturation current, e is the electron charge, k_B is Boltzmann's constant, and T is the absolute temperature. This is known as the rectifier equation. Figure 1 shows two components in the current-voltage characteristic of a Schottky diode (MATSUSHITA MA700A). The rectifier equation fits the data with $I_0 = 6.7 \pm 0.6$ nA and $k_B T/e = 27.8 \pm 0.3$ mV in a region of the forward voltage less than 300 mV. Exponential increasing of the forward current gets slow at a higher forward voltage. It seems to be due to an effect of series resistance in the diode.

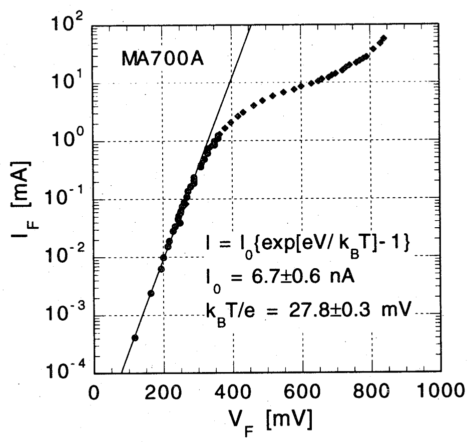

Figure 1. Current-voltage characteristic of a Schottky diode (MA700A) in the forward bias.

A test circuit using two Schottky diodes is shown in Figure 2. An RC differentiating circuit in this test circuit makes a bipolar input pulse from an input square pulse. A typical output signal (50 mV/div, 10 ns/div) is shown at the top of Figure 3 together with a bipolar input pulse (500 mV/div) at the bottom. In this measurement, a 50-MHz function generator HP 8116A was used to generate the input square pulses with a pulse width of 20 ns and a 400-MHz oscilloscope Tektronix 2467B with a probe P6133 (10 MΩ, 13.5 pF) to pick up an input pulse. The clipped pulse is followed by a differentiated pulse of the negative swing owing to the junction capacitance of the Schottky diode.

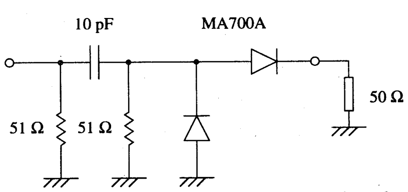

Figure 2. Clipping circuit using two Schottky diodes.

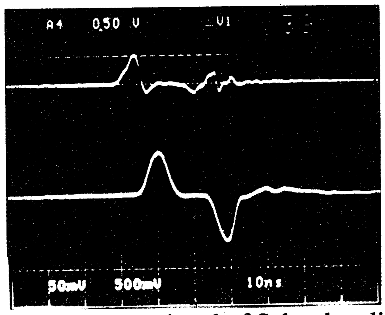

Figure 3. Typical output signal of Schottky clipping circuit (top) and its bipolar input pulse (bottom).

The linearity of the Schottky clipping circuit is shown in Figure 4. In this measurement, the same setup as that of the waveform measurement was used but the input square pulse with a pulse width of 8 ns. The clipped pulse appears when the bipolar input pulse has a pulse height over 400 mV, but the clipped pulse is smaller than the input pulse. The undershoot due to the junction capacitance has a pulse height of 20–30% of the clipped pulse. The pulse height of the undershoot is as high as that of the clipped pulse for an input pulse below 400 mV. The Schottky diode looks like an AC coupling capacitor in this region.

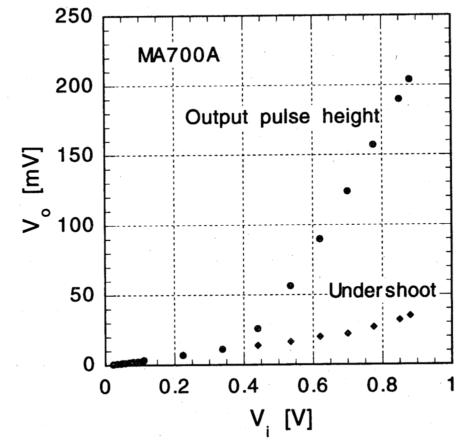

Figure 4. Clipped pulse V_o versus input pulse V_i.

Response to a faster pulse generated by a 500-MHz pulse generator HP 8131A was measured with a 1-GHz digital real-time oscilloscope Tektronix TDS684B. When a positive unipolar pulse which has a pulse width of 2.0 ns and a pulse height of 1.0 V was directly injected to the Schottky clipping circuit without RC differentiating circuit, the output pulse was a positive unipolar pulse with a pulse height of 0.5 V. When a reversed pulse was injected, a negative unipolar pulse with a pulse height of 0.5 V appeared at the output. For such a fast pulse, the Schottky diode seems to behave like a capacitor.

3.2 Clipping Circuit using Junction FET

We tried a source follower of a junction FET in the class B operation, but it had the same problem as the Schottky clipping circuit for its *pn*-junction capacitance. A common-source amplifier was investigated instead. Figure 5 shows the transfer characteristic of an FET (HITACHI 2SK291). The drain current can be theoretically written as

$$I_D = I_{DSS}\left(1-\frac{V_{GS}}{V_P}\right)^2,$$

where I_{DSS} is the saturation drain current and V_P is the pinch-off voltage. A theoretical curve fits the data very well with $I_{DSS} = 27.8 \pm 0.2$ mA and $V_P = -0.97 \pm 0.01$ V.

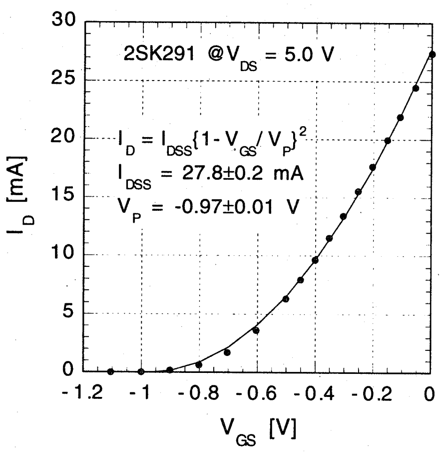

Figure 5. Transfer characteristic of a junction FET (2SK291).

A test circuit using this FET is shown in Figure 6. Same measurements as the Schottky clipping circuit were made to this circuit with the exactly same setup. This circuit has an operating point at $V_{GS} = 0.904$ V. A typical output signal (200 mV/div, 10 ns/div) is shown at the top of Figure 7 together with a bipolar input pulse (500 mV/div) at the bottom. The overshoot is very small in comparison with the clipped pulse.

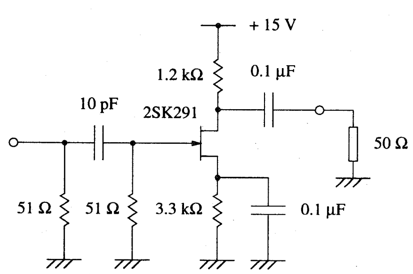

Figure 6. Clipping circuit using an FET.

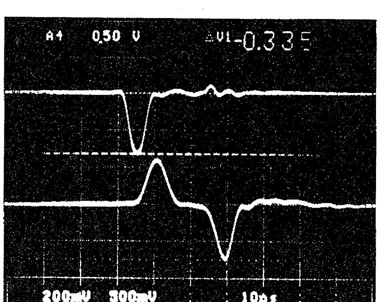

Figure 7. Typical output signal of FET clipping circuit (top) and its bipolar input pulse (bottom).

The linearity of the FET clipping circuit is shown in Figure 8. The clipped pulse appears clearly when the bipolar input pulse has a pulse height over 100 mV. The overshoot is less than 20% of the clipped pulse for an input pulse over 200 mV.

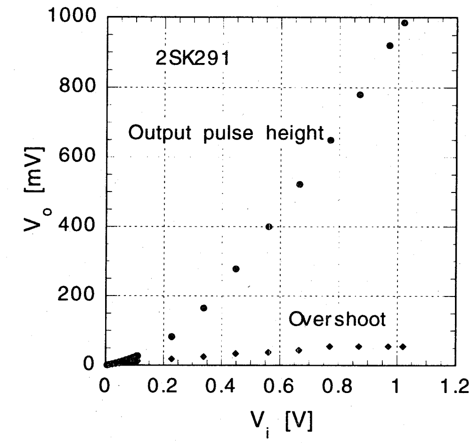

Figure 8. Clipped pulse V_o versus input pulse V_i.

Response to a faster pulse generated by a 500-MHz pulse generator was measured. When a positive unipolar pulse which had a pulse width of 2.0 ns and a pulse height of 1.0 V was directly injected to the FET clipping circuit without RC differentiating circuit, the output pulse was a positive unipolar pulse with a pulse height of 1.7 V. When a reversed pulse was injected, a bipolar differentiated pulse with a small pulse height of 170 mV appeared at the output. It seems to be due to the gate-drain capacitance.

4 Summary

We compared a clipping circuit using a junction FET with that using two Schottky diodes. The FET clipping circuit can respond to an input pulse with a pulse height over 100 mV, and has almost no overshoot in contrast with the Shottky clipping circuit. Both clipping circuits have non-linearity, but that of the FET clipping circuit is much simpler than the Schottky clipping circuit. The non-linearity of the FET circuit can be corrected with a quadratic function. Furthermore, the FET clipping circuit could respond to a fast pulse with a pulse width of 2 ns, but the Schottky clipping circuit could not. An FET has a few abilities to improve performance of the clipping circuit and to improve the position resolution of BPM.

We will test a few kinds of MOS FETs as well, because MOS FETs have smaller capacitances. In addition, the cascode connection will be tried to reduce an effect of the gate-drain capacitance. We will make a prototype clipping module using a junction or MOS FET, and will test it with beams in this autumn.

References

[1] F. Hinode et al., "ATF Design and Study Report", KEK Internal 95-4 (1995).

[2] F. Hinode et al., "A Conventional Read-out Electronics for the Button-type BPM in the ATF Damping Ring" (submitted to the 1997 Particle Accelerator Conference), KEK Preprint 97-101 (1997).