Beam Diagnoses

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Abstract

Beam diagnostic systems especially for circular electron accelerators are described. It is important to record behavior of individual bunches separately as a function of the turn number in modern accelerators. Not only several novel methods to observe beam behavior but also digital data acquisition and processing system are discussed.

1 Introduction

As accelerators become sophisticated and very small beam emittances in the three directions including longitudinal one are required, understanding of complicated phenomena due to various causes which deteriorate beam quality and their countermeasures become important. In the circumstances, beam diagnostics must play an important role. A beam diagnostic system consists of two parts, one of them is for sensing of the beam parameters and the other is for data acquisition. Various novel methods (devices) to detect the beam parameters have been developed, while development of the latter has also made rapid progress. For example, in an electron storage ring, the fast beam-ion instability (FBII) may excite the betatron motion of each bunch in spite of the existence of a gap in the bunch train to prevent the conventional ion trapping effect. The amplitude and the phase of the oscillation of a bunch depends on its position in the bunch train. In order to observe this kind of phenomenon, it is essential to record behavior of all bunches independently as a function of the turn number (a lapse of time). Recently, this kind of recording becomes practicable with the progress of digital signal processing technique including fast AD conversion and large memory capability.

Observation of transient beam behavior is often necessary to understand beam instabilities. Spectrum analyzers have been used to observe instabilities hitherto, however the method is incompetent to observe time-varying instabilities. A feedback damper which suppresses an instability can be used for this purpose. Transient beam motion is recorded using a digital data acquisition system mentioned above after the damper is turned on or off.

In section 2, various methods to detect the beam parameters are discussed. The digital data acquisition and processing systems are described in section 3, and feedback dampers are presented in section 4.

2 Detection of beam parameters

After completion of an accelerator, it is quite natural for us to want to measure machine design parameters and observe beam behavior, and it is also essential for improvement of the machine. Measurement of the beam current, the beam positions at various places in the ring, the transverse and longitudinal beam sizes (distributions of particles in the three directions if possible) and the energy of the beam is quite essential. Other machine parameters such as betatron/synchrotron tune, betatron function, dispersion function, chromaticity, momentum compaction factor and emittance can be determined using the measured beam positions, sizes and energy.

2.1 Beam Intensity, Current

Electrical or magnetic methods have been used to detect the slowly varying (frequency range of 10^{-3}Hz-10^{9}Hz) beam intensity. A DCCT is used to measure the DC beam current, and a electrostatic electrodes and loops (including current transformers with magnetic cores) are used as relatively high speed intensity monitors. However, if the bunch length is comparable or smaller than the size of the electrode, say 3mm, namely the corresponding frequency spectrum extends up to 100GHz, the property of electromagnetic wave must be taken into account in the designing of electrodes and signal transmission lines [1]. If synchrotron radiation from stored particle is available, a fast PIN photo diode or a streak camera can be used to measure the longitudinal distribution of the bunch. These optical methods can be used with a fast light shutter mentioned in section 3. Spectral analysis of the signal from the electrode for the beam intensity monitor gives the synchrotron tune.

2.2 Beam position

Measurement of the averaged beam positions along the ring is well-established and its accuracy seems to be sufficient [2]. A recent concern is turn-by-turn measurement of a bunch position. This kind of measurement becomes very easy with the progress of digital measuring instruments. An example of the injection orbit is shown in Fig.1 [3]. In the figure, the bottom graph shows the horizontal beam positions at various places in the ring at several turns after injection and the top graph corresponds to the intensity (sum of signals

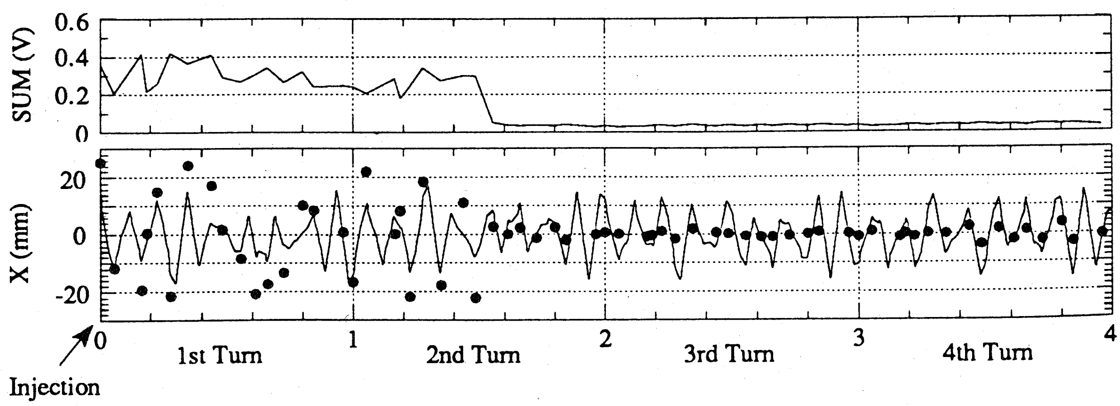

Fig. Injection orbit measured with single pass BPM

from four buttons). As the orbit was artificially deformed, the beam was lost in the 2nd turn. As seen in the figure, this technique is indispensable to launch a newly constructed accelerator with a narrow dynamic aperture.

Spectral analysis of the signal from the electrode for the beam position monitor gives the betatron tune.

2.3 Transverse Beam Distribution

Imaging the beam with synchrotron radiation has been commonly used to measure the transverse distribution in electron/positron storage ring. There are two main sources to deteriorate the resolution of the measurement: the effect of diffraction and the effect of the observation of an extended segment of the trajectory of the beam. Although the resolution for horizontal emittance measurements in the visible region is sufficient for existing storage rings, the resolution for vertical one is unsatisfactory for rings with small horizontal to vertical couplings [4]. Pin hole imaging of the X-ray is on of the solutions. An attempt to estimate the vertical beam size from a diffraction pattern has been tried [5]. Laser interferometry is also used to monitor with a nanometer spot size [6].

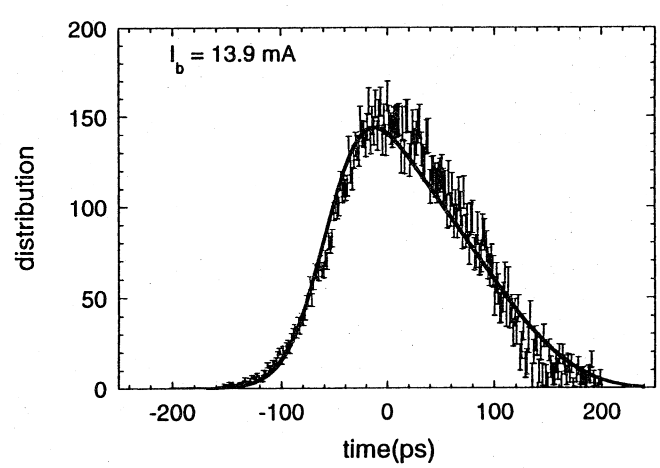

Fig. 2 Longitudinal distribution of bunch

2.4 Longitudinal Beam Distribution

Streak cameras are widely used to measure the longitudinal distribution of the beam. The photon counting method is also used for this purpose [7]. Longitudinal distributions of probe bunches that follow a main bunch with a large current are measured in order to estimate the longitudinal wake field generated by the main bunch. A large dynamic range is required for this purpose because the distributions of the probe bunches, whose currents have to be small not to interact with each other, have to be measured precisely. The photon counting system, which has large dynamic range, has been used to measure the wake field [8]. An example of the longitudinal distribution of a bunch measured with a photon counting system is shown in Fig.2 [8].

2.5 Beam Energy

The measured magnetic fields of bends are analyzed to determine the energy of the circulating beam. Since accuracy of the absolute measurement of the field is of the order of 10^{-3}, the typical error of the energy measurement has the same order. The resonant spin depolarization method was used to determine the absolute energy of the beam precisely [9]. This method can be applied to measure the momentum compaction factor which is difficult to be measured with usual methods.

3 Data acquisition and processing system

Various methods to detect the beam parameters have been developed as mentioned above, while development of digital data acquisition and processing systems has also made rapid progress. For example, in an electron storage ring, FBII may excite the betatron motion of each bunch in spite of the existence of a gap in the bunch train to prevent the conventional ion trapping effect. The amplitude and the phase of the oscillation of a bunch depend on its position in the bunch train. In order to observe this kind of phenomenon, it is essential to record behavior of all bunches independently as a function of the

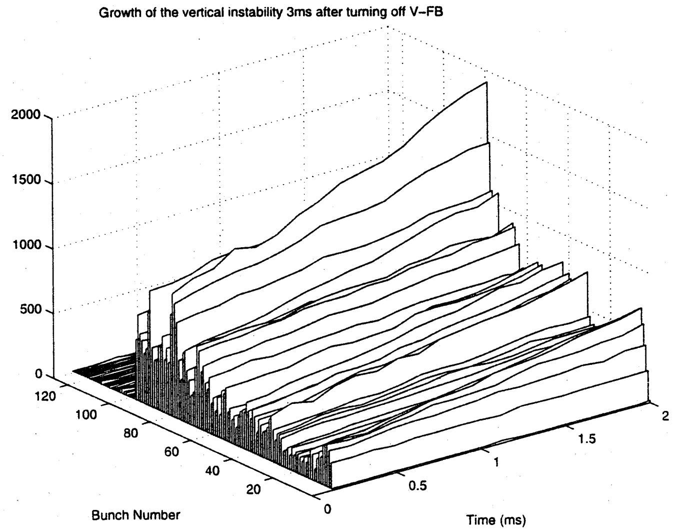

Fig.3 Vertical betatron oscillation amplitudes of individual bunches

turn number (a lapse of time) . Recently, this kind of recording becomes practicable with the progress of digital signal processing technique including fast AD conversion and large memory capability [10] , [11] .

Recent progress of bunch by bunch feedback systems which suppress the longitudinal and/or transverse instabilities using digital technique is very rapid as mentioned in the next section. The systems consist of fast A/D converters, digital memory boards with large capacity and digital signal processors. These are used as a transient analyzer which records behavior such as betatron, synchrotron oscillations or particle number (beam current) of each bunch in the bunch train. Fig.3 shows growth of the betatron amplitudes of individual bunches after turning off the vertical damper of the TRISTAN AR.

The phase spaces in the transverse and longitudinal plane has been measured using a digital transient analyzer [12] .

Usually an 8-bit ADC is used in the high speed digital data acquisition and processing system. Resolution may be insufficient in this case. As mentioned in the preceding section, optical beam monitors have several advantages compared with electrical ones: large dynamic range, high speed, high noise-immunity etc. A high speed light shutter which can be opened or closed within a bunch spacing is useful to pursue behavior of a specific bunch in a bunch train [13] . This kind of shutter using a Pockels cell has been developed recently [14] .

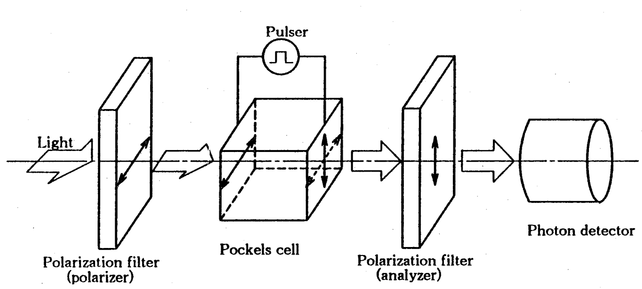

Fig.4 High speed light shutter

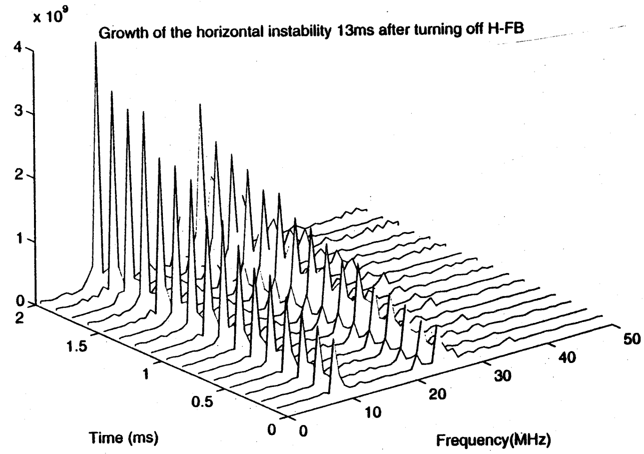

Fig.5 Growth of instability after turning off damper

4 Feedback system

Observation of transient beam behavior is often necessary to understand beam instabilities. A spectrum analyzer has been used to observe instabilities hitherto, however the method is incompetent to observe time-varying instabilities. A feedback damper which suppresses an instability can be used for this purpose. Transient beam motion is recorded using the digital data acquisition system mentioned above after the damper is turned on or off. Figure 5 shows growth of instability after turning off the vertical damper of the TRISTAN AR.

Bunch by bunch feedback dampers has been used to damp the longitudinal and/or transverse instabilities. Delay lines were used in the timing circuits of the dampers up to now, however, as machines become huge and revolution periods on which delay time depends become large, delay lines must be long and become unsuited to this purpose. Digital signal processors are introduced instead of these analogue delay lines. Progress of digital signal processing technique enables us to introduce a small number of digital filters in place of a large number of filters as many as the bunch number of the ring. Real-time digital technique seems to be indispensable to modern accelerators.

The transverse feedback system designed for the KEKB factory is shown in Fig.6.

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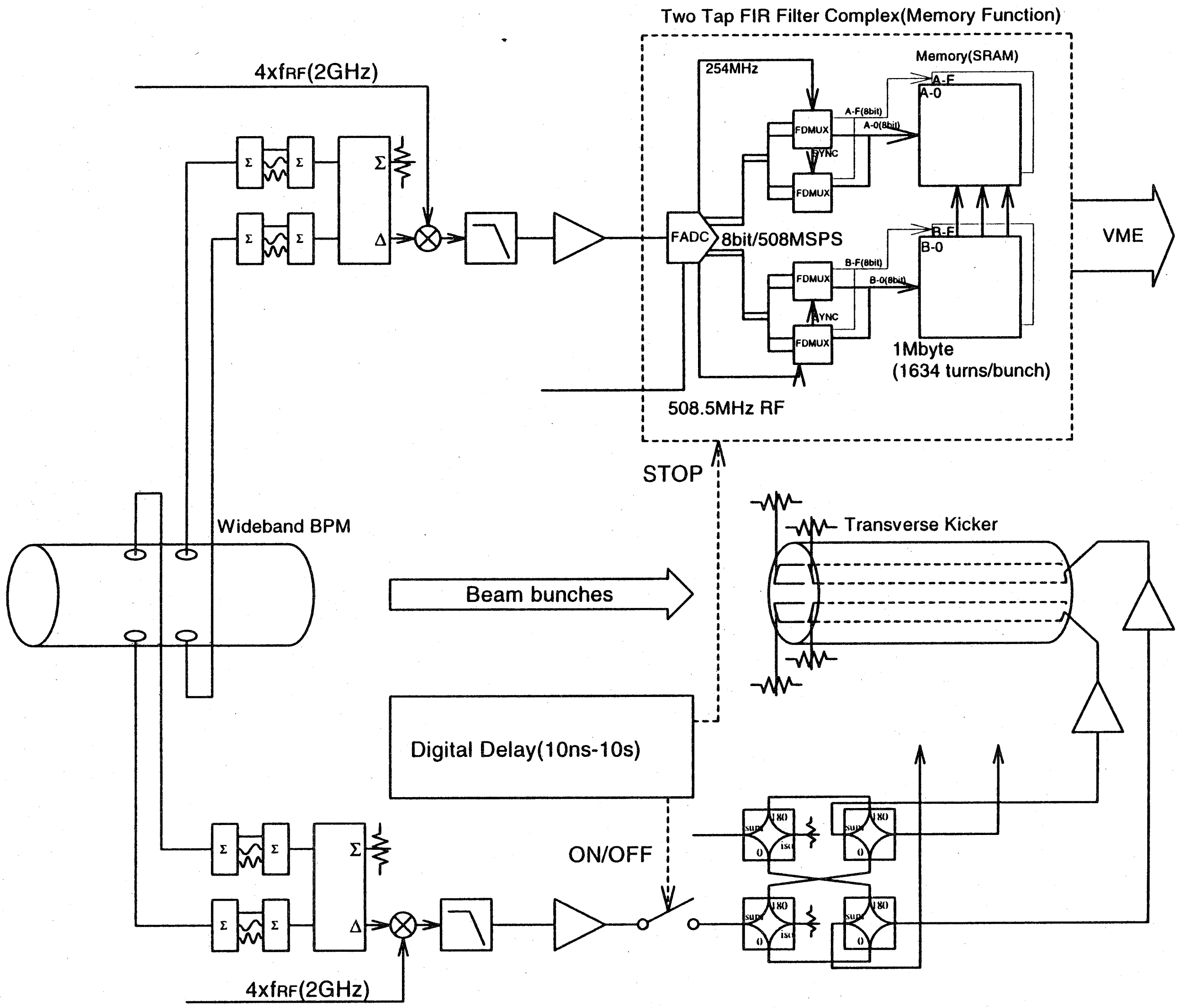

Fig. 6 Vertical damper for KEKB

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