A TUNE MEASUREMENT SYSTEM FOR LOW CURRENT AND ENERGY RAMPING OPERATION OF A BOOSTER SYNCHROTRON*

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Abstract

A betatron tune measurement system is one of the most important diagnostic tools for any circular accelerator. For the commissioning of a booster synchrotron newly developed for top-off injection into the Duke storage ring, a versatile tune measurement system employing a network analyzer, a short stripline kicker, a space filter and a photomultiplier tube has been developed to allow tune measurements over a wide range of beam energies from 0.24 to 1.2 GeV, and for low current measurements at a few micro-amperes. The signal from the highly sensitive optical detection system is also used for fast tune measurements with a real-time oscilloscope. This technique is being developed for live tune monitoring during booster energy ramping.

INTRODUCTION

The Duke Free-Electron Laser Laboratory (DFELL) operates a 0.24 to 1.2 GeV electron storage ring as a driver for UV-VUV FELs and a state-of-the-art Compton gamma-ray source, the High Intensity Gamma-ray Source (HIGS). In order to supply electrons continuously during high energy gamma production in the electron loss-mode, a 0.24–1.2 GeV booster synchrotron has been developed and successfully commissioned in 2006 [1]. This new injector is a very compact synchrotron with a circumference of 31.9 m and a maximum dipole field of 1.76 Tesla at 1.2 GeV. Because of its compact size, the effect of magnetic saturation is very significant, especially for electron beam energy above 1 GeV. Tune compensation is realized by using a number of quadrupole trims in a feed-forward scheme.

A variety of beam diagnostic systems have been developed for the booster synchrotron and related transport beamlines; details of these systems can be found in [2]. One of the critical beam diagnostics is the betatron tune measurement system. This system has been developed to achieve two goals: (1) the tune measurement system should be very versatile, capable of measuring tunes with a small current at the micro-ampere level and over a wide range of electron beam energies from 0.24 to 1.2 GeV; it also should be useful for a wide range of orbits; (2) this system should also be capable of measuring the tunes during energy ramping to track tune shift. The required high sensitivity can be easily realized using an optical detection system with a space filter and a photomultiplier tube (PMT).

At the DFELL, we had previous experience using optical signals for tune measurement; a tune measurement system employing a PMT and a razor blade was developed for the storage ring in early 1990's [3]. This system served us well during commissioning and initial operation of the storage ring. However, because of its sensitivity to the electron beam orbit in the dipole magnet where the optical signal was produced, this system was eventually replaced by a more conventional system which utilized a stripline kicker as a pickup for tune signals, making it completely independent of beam positions. Reflecting on this experience, we have developed an improved optical detection scheme for the booster tune measurement system to overcome the shortcomings of the older system.

SCANNING TUNE MEASUREMENT SYSTEM

The layout of the booster scanning tune measurement system is shown in Fig. 1. This measurement system can be divided into two subsystems: a tune excitation system and an electron beam signal detection system. These two systems are connected to and coordinated by a network analyzer which provides the RF signal for excitation and simultaneously measures the beam response to determine betatron tunes.

The tune excitation system consists of an RF signal source (inside the network analyzer), an RF mixer, a low power amplifier (2 W), and a 3 cm long stripline BPM as the kicker [4]. In the old tune measurement system for the storage ring [3], because of the choice of a very low excitation frequency (< 2 MHz typically), a ferrite transformer was necessary to provide improved impedance matching to drive the DC-shorted BPM striplines. The new system does not require an impedance matching transformer; instead, it drives the BPM striplines with a higher RF frequency around 179 MHz by taking advantage of the reasonably large impedance at this frequency for the stripline BPM. The excitation signal is produced by mixing the low frequency drive signal from the network analyzer (typically < 2 MHz) with the booster RF cavity signal at 178.55 MHz. The mixed signal is then amplified and applied to the BPM striplines. This new arrangement has allowed us to achieve a large dynamic range of excitation. It is also important to mention that the striplines are connected in an asymmetric manner: more signal is used to drive the beam horizontally. This arrangement is necessary to compensate for the mismatched beta functions, $\beta_x \ll \beta_y$, with $\beta_x = 4.6$ m and $\beta_y = 27.2$ m at the location of the stripline BPM.

Synchrotron radiation from one of the dipole magnets is used by the beam signal detection system. This system con-

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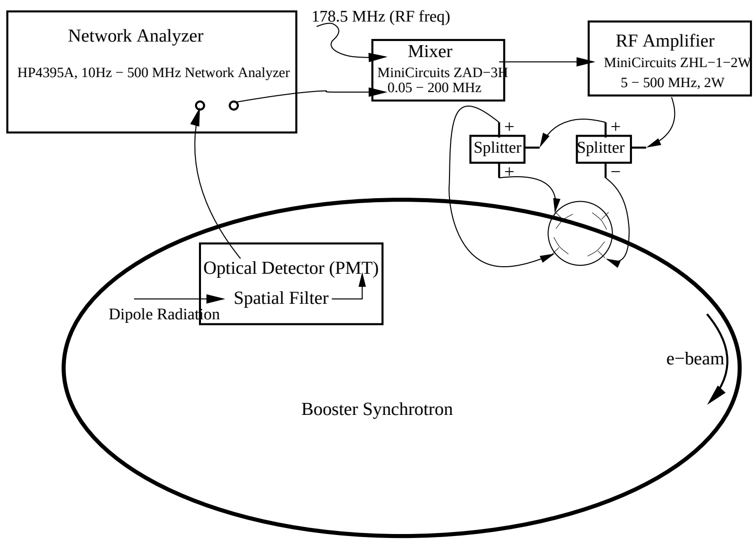

Figure 1: The layout of the booster scanning tune measurement system. A network analyzer excites the electron beam using a stripline BPM and the beam response signal is detected by an optical system with a space filter and a PMT.

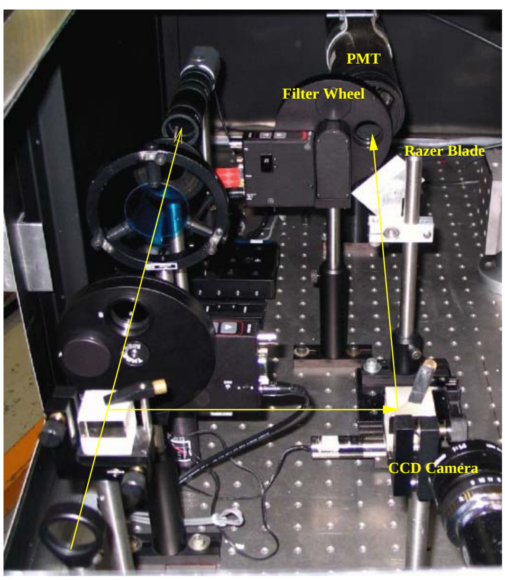

Figure 2: The optical detection system. The optical beam from a dipole synchrotron port passes a space filter (a razor blade) before being detected by a photomultiplier tube.

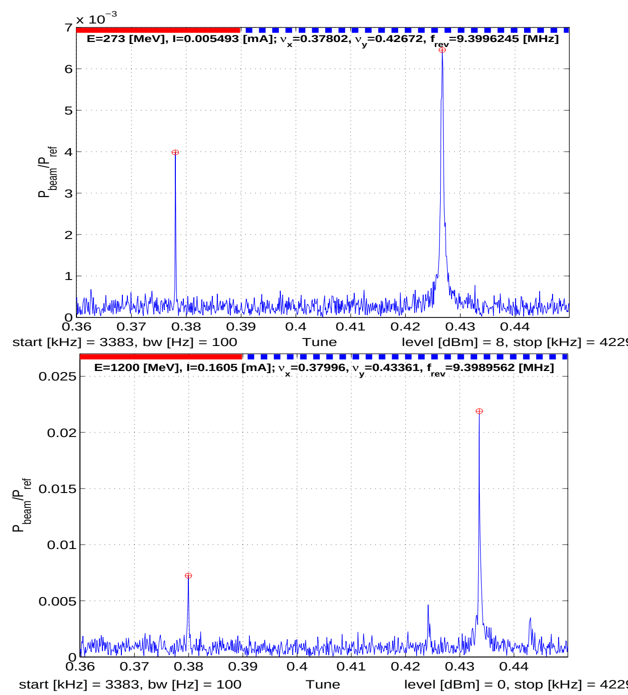

Figure 3: The measured betatron tune signals. The upper plot shows the measured tunes at the injection energy of 273 MeV with about 5 μA of stored beam current; the lower plot shows the measured tunes at the highest extraction energy of 1.2 GeV with about 150 μA of stored beam current.

sists of a focusing lens, a space filter (a razer blade), a neutral density filter array, a photomultiplier tube, and a CCD camera. By cutting the optical beam in half, the 45-degree mounted razer blade is used as a space filter to provide intensity modulation of the optical signal before it enters the PMT. One of the critical difference of this new system from the old one [3] is that the optical beam is deliberately defocussed on the razor blade to a spot size of about 2 mm. This arrangement makes the optical detection system much less sensitive to the motion of the source of the light, i.e. the orbit motion in the booster. In fact, this setup allows us to measure betatron tunes without any adjustment of the razor blade for normal operation of the booster at various energies. Occasional adjustment of the razor blade position was necessary during commissioning for unusually large orbit distortions. This was accomplished by using a CCD camera to monitor the position of the optical beam on the razor blade, while adjusting the position of the blade which is mounted on a 1D motion stage with remote control. The dynamic range of the signal detection is further extended by (1) implementing a remote control for the PMT high voltage power supply; (2) installing a remotely controlled neutral density filter wheel system.

These improvements over the old system have significantly increased the versatility of this scanning tune measurement system. It has been successfully used for commissioning and operations over a wide range of beam energies and lattice conditions. It has been used successfully to measure tunes in the entire range of the booster operation from 0.24 to 1.2 GeV (see Fig. 3). Furthermore, it is capable of measuring tunes with very low beam current as low as a few micro-Amperes (see the upper plot in Fig. 3). This system has also been used to measure other important beam parameters such as chromaticity and linear coupling.

FAST TUNE MEASUREMENT SYSTEM

The highly efficient operation of a booster synchrotron requires the avoidance of large tune shifts which can cross strong resonances during energy ramping. This is a very challenging task for this unusually compact booster with highly saturated magnets. Substantial effort has been devoted to developing an elaborate tune compensation scheme for the entire energy range of booster operation [1]. This compensation scheme was implemented in the low level controls of the EPICS based control system [5]. The effectiveness of tune compensation can be checked by stopping the booster ramp at various energies and measuring tunes using the scanning tune measurement system. This simple technique was successfully used in the booster commissioning. It worked well because we developed this booster as an accelerator with dual operation modes [5]: (1) as a storage ring; (2) as an energy ramping synchrotron. Nevertheless, a fast tune measurement system can be very useful for monitoring tune shifts during ramping. It can be a critical diagnostic tool for other booster synchrotrons which do not have a storage-ring mode of operation.

The fast tune measurement system is still being developed at the DFELL. Presently, this system employs the same optical detection as the scanning tune system (see Fig. 2). The betatron tune is excited by the vertical injection kicker and detected by the PMT. The PMT signal is measured by a real-time digital oscilloscope with a deep memory (a 1 GHz LeCroy WavePro 7100A). Fig. 4 shows such a fast tune measurement—after storing the electron beam at the injection energy of 273 MeV, the vertical injection kicker was lowered to 1 kV and fired, and the recorded beam signal was analyzed using FFT. Clearly, both vertical and horizontal tunes were excited even though the excitation kick was vertical. Furthermore, we notice that due to the decoherence effect, the vertical and horizontal tune signals fade into background after about 1 and 2 ms, respectively.

Further development is in progress to make this fast tune measurement system useful for real-time tune monitoring during booster ramping. Two ideas will be tested to overcome the decoherence effect: (1) to repeatedly kick the beam using the injection kicker at a high repetition rate, about 25 Hz; (2) to continuously excite the beam during ramping using a broadband drive signal.

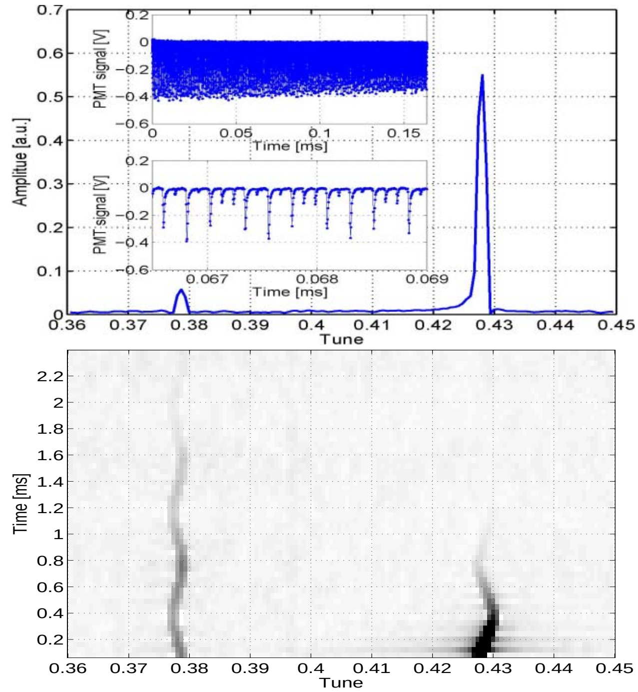

Figure 4: The betatron tunes measured using a real-time oscilloscope. In the upper plot, both tunes, $\nu_x = 0.378$, $\nu_y = 0.428$, are plotted together with the corresponding time-domain signals: the upper inset shows a full slice of time domain signal used for FFT analysis; the lower inset shows a selected portion with visible peak modulation. The lower plot shows the evolution of betatron tunes after excitation.

CONCLUSION

We have developed a versatile scanning tune measurement system for the booster synchrotron with a wide dynamic range in terms of beam current and beam energy. By optimizing the optical detection system, the tune measurement system is less sensitive to orbit changes in the booster. We have also demonstrated the capability of a fast tune measurement system; further development is in progress to use it for tune monitoring during booster ramping.

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