THE ROLE OF BEAM DIAGNOSTICS IN THE RAPID COMMISSIONING OF THE TPS BOOSTER AND STORAGE RING

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Abstract

The TPS is a newly constructed 3-GeV third-generation synchrotron light source featuring ultra-high photon brightness with extremely low emittance. After some hardware improvement especially demagnetization of chamber are completed, the commissioning of the beam in the booster ring began on December 12 and attained 3-GeV energy on December 16. The storage ring obtained its first stored beam and delivered synchrotron light on December 31[1][2]. This report summarizes the role of beam diagnostic for hardware improvement and parameter tuning during TPS successful commissioning.

INTRODUCTION

The TPS accelerator complex consists of a 150 MeV S-band linac, linac to booster transfer line (LTB), 0.15–3 GeV booster synchrotron, booster to storage ring transfer line (BTS), and 3 GeV storage ring. The linac was a turn-key system delivery by RI GmbH. The booster and the storage ring share the same tunnel in a concentric fashion. The booster has 6 FODO cells and its circumference is 496.8 meters. The Storage Ring's circumference is 518.4 meters with 24 DBA lattice and 6-fold symmetry [3].

To catch up the delayed schedule due to construction delay, it was decided to perform system test and beam commissioning in parallel just after get operation permission from government authority in mid August. After solved overheating problem of the booster dipole power supply and optimize post-pulse residual field of the booster injection kickers, multi-turn circulating beam was observed in the booster synchrotron in beginning of September. These hardware problems are mostly due to the limited rush time before operation. However, the captured and stored beam intensity is decay exponentially even any kind of efforts were did such as orbit optimization, add extra correctors, chamber and magnet re-alignment and etc. Finally, it was recognized the relative permeability (ranging from 1.2 to 2.0) of the pipes arising from the cold-drawn process of the booster vacuum pipe was too large on November 12. After dismantle vacuum pipe, heat treatment, and re-install again, beam was stored successfully on December 12, energy ramp to 3 GeV on December 16. Later, after improving field leakage of booster extraction DC septum, we had a 5-mA stored beam on Dec. 31 2014. Diagnostic system played a helpful rule to provide beam profile and information to improve or tune subsystem to make progress quickly during beam commissioning. This report will brief about diagnostics for TPS.

SCREEN MONITOR

The screen monitor system is the most import destructive monitor during the TPS beam commissioning. There are 33 screen monitor systems distributed around Linac (5), LTB (5), booster synchrotron (7) , BTS (5), storage ring (4), and frontend (7). The screen monitor is responsible for the beam profile acquisition from fluorescent screen and used to analysis to find the beam characteristic data. The beam profile image has extensive information on beam parameters, including beam center, sigma, tilt angle and etc. The system contains YAG:Ce screen, lens, lighting system, LEDs illuminator, and GigE Vision CCD camera. A pneumatic device is used to move the whole assembly in or out. All of these devices are controlled remotely including the CCD power control, screen in/out control and LED lighting system. The camera timing trigger clock is locked with TPS injection system, which is produced from a local timing IOC (EVR). Based on the area Detector module which provides a general-purpose interface for area (2-D) detectors in EPICS, it is easy to construct a camera control panel by using the EDM, and analysis tool by using the Matlab tool. Figure 1 shows the beam profile observed at booster 1st screen monitor.

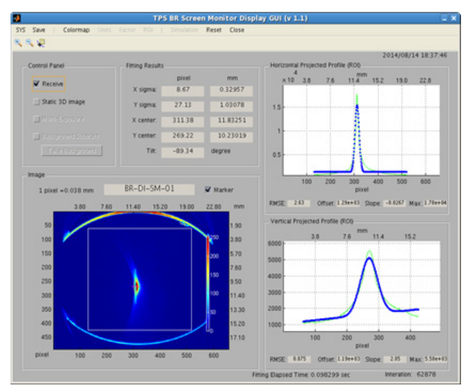

Figure 1: Beam profile at booster 1st screen monitor.

INTENSITY MONITOR

Linac contracted to RI GmbH is provided two Faraday cups and two warm current monitors. Figure 2 shows bunch waveform observed by the wall current monitor just after electron gun. There are two ICTs and two FCTs for LTB, two ICTs and one FCT at BTS where Figure 3 shows ICT waveform at LTB for single bunch beam and

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Figure 4 shows the booster current via FCT VNC display. The beam trips when ramping down to 2 GeV due to tune cross resonance line. The booster equipped with one DCCT and one FCT.

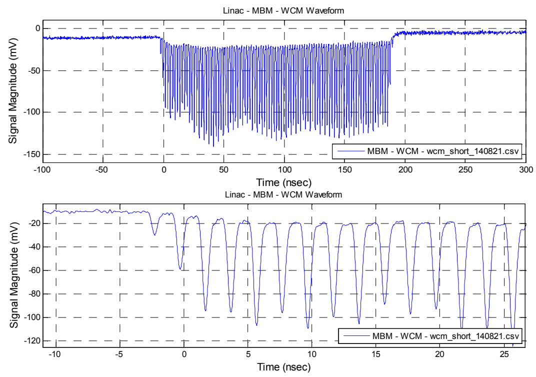

Figure 2: Bunch waveform observed by the wall current monitor just after electron gun.

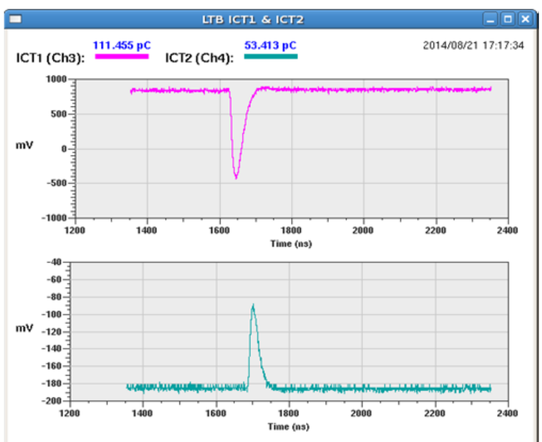

Figure 3: ICT waveform at LTB for single bunch beam.

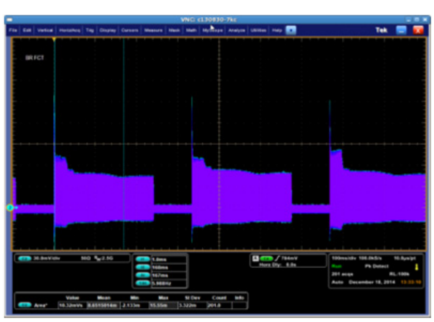
Figure 4: FCT display for booster ramping.

Data acquisition of the storage ring DCCT is via with high precision ADC and digital multi-meter used to measure beam current from DCCT. Lifetime is calculated by regression from measured beam current. Injection efficiency estimation and injection sequence control is to use information of the measured beam current as well. Only single NPCT was installed at the storage ring, to prevent possible fault resulting in another problem, a tone loop winded on NPCT is to detect correction of the devices and connected to machine protection system.

Signal from BPM pickup and synchrotron light are both used to measure filling pattern. Figure 5 shows the filling pattern measured from pickup and TSCPC respectively. High resolution oscilloscope to observed signal from FCT at the booster synchrotron and BPM buttons at storage ring are used to provide information of filling pattern. Time-correlated single proton counter is also available at the storage ring synchrotron light diagnostics port. There monitors can provide bunch current information and also measure single bunch purity with high dynamic range as Figure 6 shown.

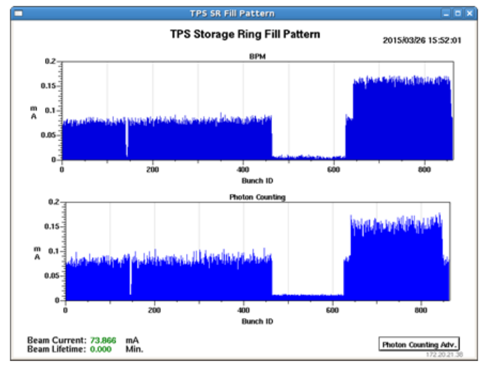

Figure 5: Filling patterns of the storage ring are measured from BPM button (upper) and TCSPC (lower).

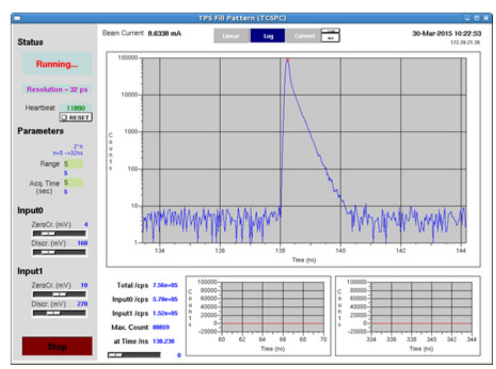

Figure 6: Single bunch impurity is achieved 10^{-5} by using bunch cleaning observed by TSCPC.

BEAM POSITION MONITOR

BPM is the major diagnostic device for beam commissioning. The electronics adopt commercial product Libera Single Pass Brilliance and Libera Brilliance Plus [4]. Linac optimization had much depended on BPM and the first turn of the booster beam had achieved and observed by BPM soon after correctors steering. There are only few buttons of booster BPM found to have contact problems quickly by observing ADC data with extremely low count compared to other buttons. The real BPM calibration factor was agreed with the designed values by measuring and comparing the optical function of machine model. Beam transport efficiency at BTS achieved up 90% estimated by BPM. The first turn and accumulated beam of the storage ring

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soon obtained without correctors after injection started. It was also found that there are some cabling problems during measure and optimize machine. Button B and C of two BPMs are cross connected. The cables of BPM 24_4 and 24_6 are also connected in wrong order. Besides, the LOCO fitting for BPM calibration factor showed that there are three primary BPM located near RF cavity which the fitting factors Kx/Ky are almost only one half of the expected value. It was caused by incorrect set to the configuration of the primary type BPM while they should have configurations of the standard type [5].

LTB & BTS

There are seven and six BPM installed at LTB and BTS transport line. Both are elliptical shape with chamber dimensions of 56x28 and 35x20 mm and button diameter of 10.2 and 10.7 mm for LTB and BTS respectively. The commercial product – Libera Brilliance Single Pass are adopted to provide measured data with EPICS support. Figure 7 shows the GUI main page for BTS transport line. BPM ADC data and detail configuration could be also accessed in the below pages.

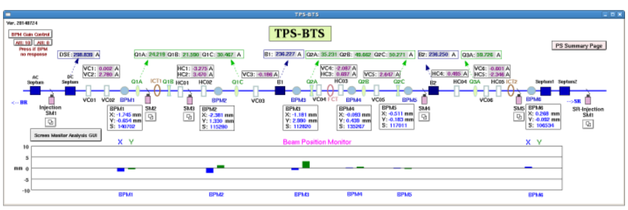

Figure 7: BTS GUI main page. BPM ADC data and detail configuration could be also accessed in the below pages.

Booster Synchrotron

The TPS booster ring has six cells where each cell is equipped with 10 BPMs which can be used to measure beam position and rough beam intensity along the longitudinal position and tune measurement. The mechanical dimension of booster BPM shapes 35x20 mm elliptical and button diameter 10.7 mm. For TPS booster BPM, there are 60 sets of phase-trimmed 0.240" form polyethylene coaxial cables connected between the buttons and BPM electronics. The BPM electronics Libera Brilliance+ are adopted for both booster and storage ring of TPS and provides various BPM data flow for diverse functionalities and purposes. In this section, different BPM data flow will be demonstrated for different applications.

The ADC raw data is useful for checking the timing of the beam and beam property especially in the first turn. The phase delay due to time difference when beam travel pass the buttons along the ring could be aligned by ADC clock offset. The timing of kicker and septum trigger are also adjusted by compared to BPM ADC signal as Figure 8 shows which the first turn of BPM should be located between the pulse of the kicker waveform.

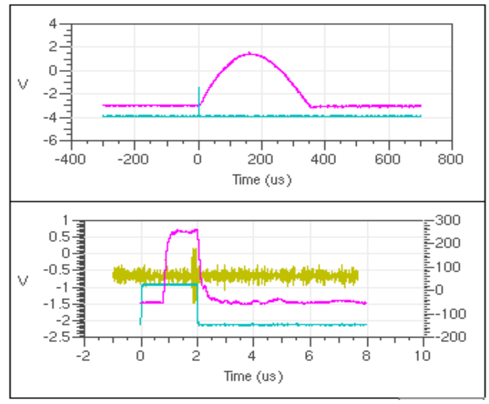

Figure 8: The upper plot is septum waveform (pink) and its trigger (blue). The below plot is kicker waveform, its trigger and ADC data of booster 1st BPM button D (yellow) located between the pulse of kicker waveform.

BPM electronics provides single pass mode for calculating first turn trajectory from ADC data. However, vast beam losses and ADC DC offset up to 100 count will result in worsen signal to noise ratio and position calculation offset error. Therefore, a soft IOC would be applied to acquire more precise first turn trajectory from ADC raw minus DC offset. Figure 9 shows the first turn orbit trajectory and sum along 60 BPMs. Horizontal trajectory shapes like dispersion function due to energy drift from Linac modulator.

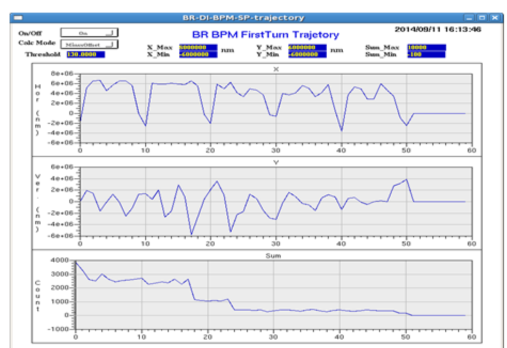

Figure 9: First turn horizontal, vertical trajectory and sum along 60 BPMs of booster. Horizontal trajectory shape like dispersion and it indicates the injection beam energy is higher that dipole current settings.

DDC (Digital Down Converter) and TDP (Time Domain Processing) Turn-by-turn data are both provided by BPM electronics and the resolution could achieve around 150 um at 0.5 mA. The BPM TBT data could be applied to extract tune as well as calculate optical function more efficiently. To use TDP properly, phase offset should be adjusted by beam according ADC data and mask window also should be set correctly according bunch length. Compared to DDC, TDP could well resolve beam loss status and tune extraction due to clear and no smear TBT data [5].

The BPM electronics also provide 10 kHz fast position

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data to measure average stored beam orbit. It shows orbit variation during ramping could be around 6 mm in horizontal and 2 mm in vertical. The low frequency synchrotron motion around 1.5 kHz is contributed for the injection initial variation [5]. The related applications including GUI and acquiring scripts are developed and provided for studying and helping commissioning.

Storage Ring

The TPS storage ring is divided into 24 cells and there are 7 BPMs per cell. Another six BPM are also installed at three straight lines located with double minimum betay quadrupels for local measurement. There are two kinds of BPM for storage ring: one is standard button BPM shapes 68x30 mm elliptical and diameter 7.4 mm at arc section; the other is primary BPM shapes 64x16 mm racetrack and diameter 7.4 mm at straight line. The calibration factor Kx/Ky is 13.8/12.73 and 6.58/8.89 mm for standard and primary BPM respectively.

BPM electronics also provides several data type for different application. ADC and TBT data is acquired on demand by trigger; 10 Hz slow data is for DC average orbit and 10 kHz fast data could be applied for stability analysis and fast orbit feedback application.

After beam stored, the beam current had achieved 50 mA in March 2015 with vacuum pressure dropped. However, it was hardly continuously accumulated and beam trip happened. It was later verified that synchrotron motion is the major reason due to RF feedback loop resonance. The BPM turn-by-turn data observed that the synchrotron motion make horizontal position vibration at same phase as Figure 10 shown and it became stronger as beam current increased.

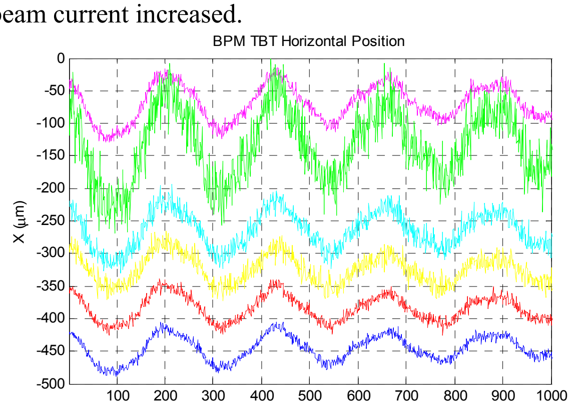

Figure 10: Horizontal TBT data. The synchrotron motion's amplitude for each BPM is proportional to its dispersion and also increased as beam current increased.

TBT data is also applied to extract tune in the storage ring. Besides injection kickers, the horizontal and vertical pingers are used to excite beam motion in two planes respectively. Timing for trigger of BPM, kickers and pingers are controlled by event system. Figure 11 shows the real time tune display page. The chosen BPM, average number, FFT length and etc. could be selected according to different condition and requirement.

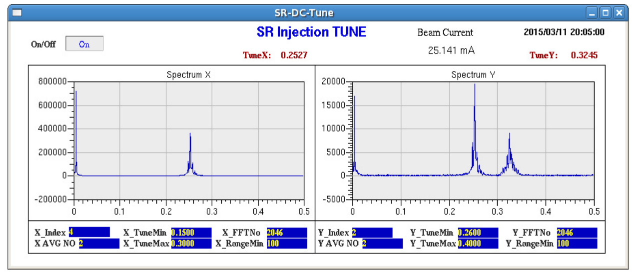

Figure 11: Storage ring tune extracted from BPM TBT data where beam are excited by pingers.

10 kHz FA data could be provided to analyse transient motion, orbit stability as well as applied for fast orbit feedback. The synchrotron motion around 2 kHz could be also observed. According to BPM spectrum from FA data, 29 Hz noise was found the dominant noise source induced from turbo-pump motor. Booster extraction at 3 Hz repetition rate also makes 3 Hz noise observed. Besides, water flow also causes wide band vibration from 30 to 70 Hz. Figure 12 shows the integrated PSD for the horizontal and vertical planes. Efforts to eliminate the noise source will be undertaken in the future.

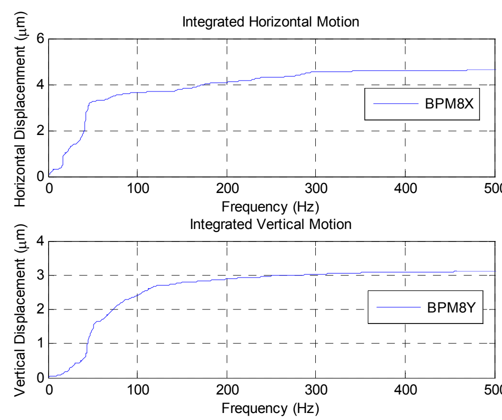

Figure 12: Horizontal and vertical integrated PSD.

Moreover, BPM FA data of the storage ring are also used for interlock safety of position and angle. BPM electronics itself provide position interlock functionalities. Another dedicated IOC is adopted to calculate all angles between different BPM from streaming in FA data through Gigabit Ethernet and activates interlock.

TUNE MONITOR

Booster Synchrotron

Originally during booster commissioning beginning in Sep. 2014, the magnetic shakers where two multi-turn coils are mounted on vacuum chamber in horizontal and vertical plane are applied to excite beam. The kickers with 50Ω terminated load have calibration factor of 3 mG/A and are driven by a 50W amplifiers. Later, the stripline electrodes are adopted to replace magnet shakers

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on the booster synchrotron considering more power strength to excite beam. The TBT data provided by BPM electronics would be acquired to extract tune by FFT. Agilent arbitrary signal generator would provide band-limited, strength-adjustable excite signal. The functional block diagram of this new tune monitor system is shown in Figure 13. Figure 14 shows the tune measurement GUI. The tune variation was as large as 0.25 for horizontal and 0.2 for vertical before tune compensation. It could be inferred that reference waveform generated from the measured I-B table provide by the magnet lab could be deviated from the actual machine.

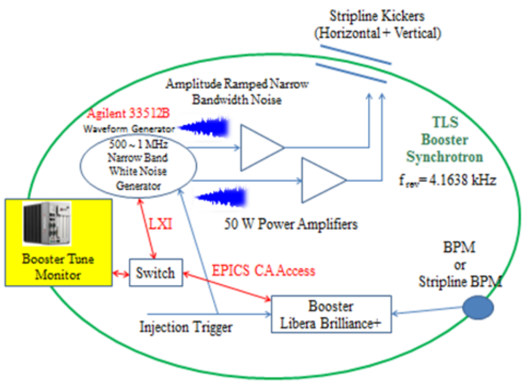

Figure 13: Functional block diagram of the tune monitor for TPS booster.

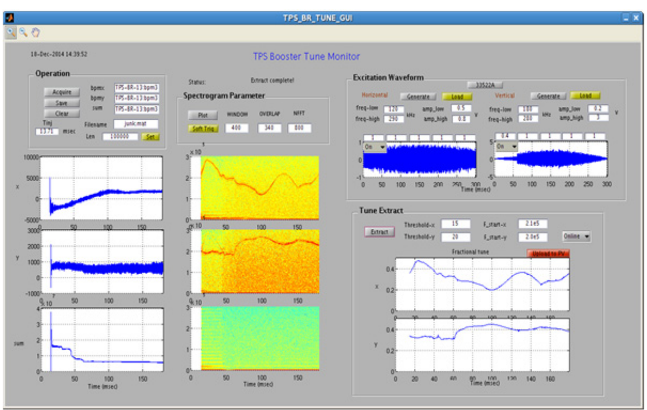

Figure 14: Tune monitor during Booster ramping before tune compensation. Vertical tune variation was as large as 0.25.

Storage Ring

Residue beam motion during injection caused by injection kickers, or shaking beam by dedicated horizontal and vertical pingers are used to excite beam motion in two planes respectively. Timing for trigger of BPM, kickers and pingers are controlled by event system. The TBT data provided by BPM electronics would be acquired to extract tune by FFT. The chosen BPM, average number, FFT length and etc. could be selected according to different condition and requirement. Figure 15 shows the real time tune display page.

Tune can also be measured by the bunch-by-bunch feedback system. Notch in the averaged spectrum after close feedback loop can use to indicate working tune. Single bunch excitation and perform FFT can also extract tune. Single bunch excitation will not deteriorate stored beam quality.

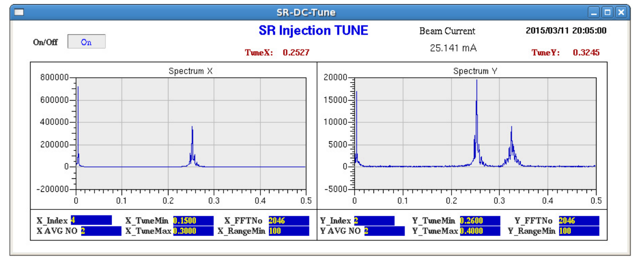

Figure 15: Storage ring tune extracted from BPM TBT data where beam are excited by pingers.

SYNCHROTRON RADIATION MONITOR

Booster Synchrotron

The synchrotron light monitor was designed. The light leads to the wall via a four-piece adjustable mirror, focusing through a lens and band-pass filter to GigE Vision camera. The camera trigger is synchronized with the machine cycle; change the delay time will change the energy point of observation. A 1-inch size CCD is used to quickly and easily to find a first-time beam spot. This synchrotron light monitoring port was used for streak camera measurement for linac beam and booster stored beam also.

The shape and size of the electron beam profile vary during the energy ramping from 150 MeV to 3 GeV, as shown in Figure 16. The beam size in both axes decreases when the energy increases due to radiation damping clearly (see Figure 17). This result is consistent with the design [3][6].

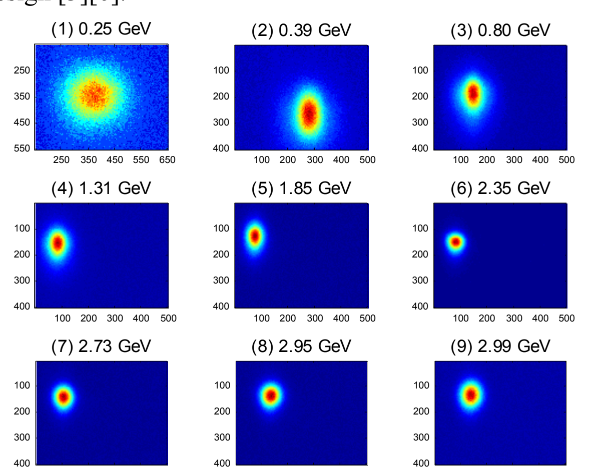

Figure 16: TPS booster synchrotron radiation profiles at varied energy ramping point, 1 pixel is around 9 µm.

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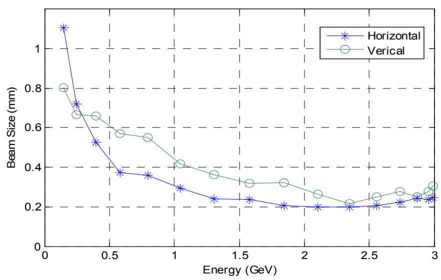

Figure 17: Measured variation of beam size with energy ramping of booster synchrotron.

Storage Ring

The photon diagnostics beamline utilized visible light and X-ray of the synchrotron radiation which generated in a bending magnet. The X-ray pinhole camera design for imaging the electron beam from bending magnet for the beam size and emittance measurements. They offer the required resolution and the dynamic range to measure the electron beam size accurately at all currents. The visible light of synchrotron radiation was design for streak camera, interferometer and fill pattern measurements.

The beam size of single bunch measured via X-ray pinhole camera in low current (~2 mA) is 39.1±0.6 µm in horizontal and 15.7±1.5 µm in vertical. When the storage beam current increases, the beam size of the horizontal axis also increases, but the vertical axis is no significant change. The CCD exposure time is reduced (~10 ms) to avoid the measurement error caused by the beam oscillation due to mechanical vibration. The calculated emittance and coupling are $\varepsilon_x \approx 1.64$ nm·rad, $\varepsilon_y \approx 15.7\pm3$ pm·rad, and $k \approx 0.96\%$ [6]. The TPS design natural emittance (ε_{x0}) is 1.6 nm·rad.

Streak Camera Measurement

For the bunch length measurement, the synchroscan unit of 250 MHz is used. The result shows that the bunch length of the TPS storage ring is around 11.4 psec (sigma) in low current (~0.2 mA) single bunch mode as Figure 18. When the current is increased, the bunch length is also significantly increased.

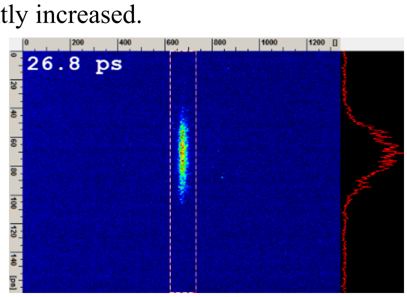

Figure 18: Typical streak image of bunch length measurement at TPS storage ring under single bunch mode.

BEAM LOSS MONITOR

In the booster ring, the radiation-sensing field-effect transistor (RadFET) is installed before the fifty-four bending magnets of the booster synchrotron in six cells to monitor the beam loss during beam commissioning [7]. Nine RadFETs in each cell are collected by a reader. Six readers and the controlling IOC is linked with a private virtual LAN [8]. The accumulated dose, dose rate and beam loss distribution are published and shown in the control system online. The typically beam loss distribution during booster commissioning is shown in Figure 19. The six RadFETs are installed in the inside-wall chamber of the storage ring in each cell. One reader is setup in the cable tray of the tunnel to minimize the cable length from RadFETs to the reader.

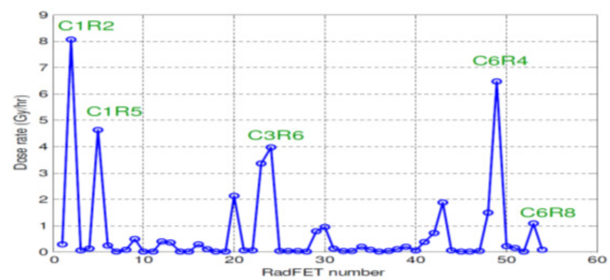

Figure 19: Beam loss distribution of booster ring during beam commissioning.

Several kinds of beam loss monitor were installed. Bergoz's PIN diodes beam loss monitor (BLM) was installed at the storage ring in June. The six Bergoz PIN diodes are installed in the inside-wall chamber of the storage ring in each cell Multichannel scaler data acquisition system were sat up a tested in July. The output pulse of PIN diodes is coupled via pulse transformer and send by twisted pairs cable (UTP/STP) to a differential receiver to convert to LVTTL pulse to compatible with input of the data acquisition system. The data acquisition consists of a 16 channel multichannel scaler in Industry Pack form factor installed on cPCI carrier board of a cPCI EPICS IOC on the equipment area. All scalers which distributed at 24 IOCs are synchronized by the timing system of the accelerator. Commissioning of this system is scheduled in September.

Several high counting rate BLMs such as scintillation detectors and Cerenkov detectors are also installed in the first cell below the injection straight for preliminary studying.

ORBIT FEEDBACKS

Fast correctors just installed June 2015. The firmware modification of fast orbit feedback is still underway. TPS will first provide a simple slow orbit feedback system which is implemented by Matlab script to support insertion devices commissioning with 10 Hz updating rate during 4th quarter 2015. All components for fast orbit feedback system would be installed in last several months as well. Testing is on going to ensure every component is working properly. Fast orbit feedback will commission in adequate window in late of 2015.

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BUNCH-BY-BUNCH FEEDBACKS

A simple two parallel stripline prototype vertical kicker was installed at the storage ring rather than real kickers will used due to implementation schedule cannot be met. Preliminary test of the vertical bunch-by-bunch feedback was performed. Commercial feedback processor (iGp12) was used for TPS. The feedback loop was closed in mid-January [9]. Preliminary test were performed despite very strong energy oscillation existed. Various functionalities of the bunch-by-bunch system were examined. Figure 20 shows the typical grow/damp experiment of the 90 mA stored beam. Resistive wall instability is the major cause. Adequate damping is achieved. Single bunch purity is bad during several shift for parameter measurement, bunch clean is performed to keep bunch purity better than 10^{-5}.[6]. Two vertical kickers and one horizontal kicker which are derived from the design of SLS/ELETTA were implemented and installed for the preparing next phase commissioning. Co of bunch-by-bunch feedback by using new kickers is schedule after beam stored in September.

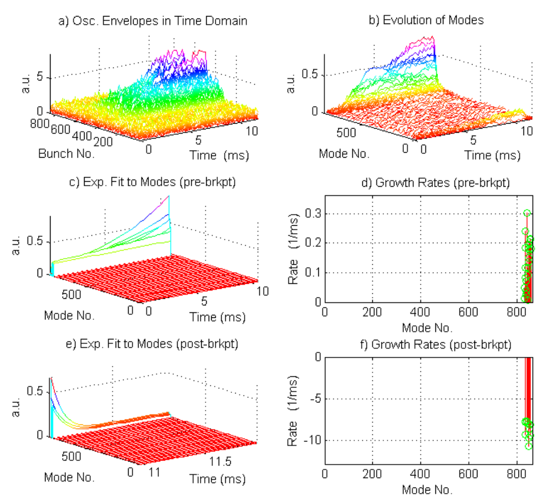

Figure 20: Grow/damp data shown that the adequate damping is achieved for 100 mA beam current.

MACHINE PROTECTION SYSTEM

To protect accelerator from damage for miss-steering of the beam, beam position as well as angle interlock are implemented. The beam position interlock is implemented at the BPM platform. Beam angle are calculated at a dedicated PC running Linux to receive BPM grouping data, then calculated beam angle at 10 kHz rate. The PC also are installed EPICS IOC to serve as interface of the 10 kHz loop as man-machine interface. Configuration of the operation can be set via EPICS channel access.

CURRENT STATUS

Phase I commissioning was proceeded with two Petra cavities and without insertion devices during December 2014 until March 2015 to examine feasibility and validity of the design of accelerator system. Beam was stored up to 100 mA very soon. Various measurements were performed. Diagnostics play an important role during commissioning in all-round aspects. Two KEK-B superconducting RF cavities and the 7 sets of in-vacuum undulators and three sets of elliptically polarized undulators had been installed during shutdown from April to late August 2015. Phase II commissioning is started from 2015 September. Diagnostic provide quite a lot of beam information during commissioning as well as future optimization.

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