THE BEAM DIAGNOSTICS SYSTEM FOR J-PARC SYNCHROTORONS

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Abstract

The beam diagnostics system for the synchrotrons of the J-PARC is described. The system design is adopted for high current machines with low beam loss and commissioning strategy. Some test results are reported.

INTRODUCTION

There are two proton synchrotrons in J-PARC (Japan Proton Accelerator Research Complex), the 3GeV Rapid-Cycling Synchrotron (RCS) and the 50GeV Main Ring synchrotron (MR). Each machine provides large beam power of 1MW and 0.75 MW with 8.3×10^{13} and 3.3×10^{14} protons per pulse, respectively. Their circulating currents reach 11.1 A and 12.8 A. The ring circumferences are 348m and 1565m each. The machine repetition rates are 25Hz and about 0.3 Hz. The proton is injected at 400MeV (181MeV at Day-1) into the RCS and fast extracted at 3GeV. The revolution frequency varies from 614 (469) to 836 kHz at the RCS and 186 to 191 kHz at the MR. Similarly, the RF frequency changes from 1.23 (0.94) to 1.67 MHz, and 1.67 to 1.72 MHz.

A pulse-bending magnet, which is installed at 15m downstream of the RCS extraction, switches the proton beam every 3 seconds, to two beam transport lines. One is called 3NBT which transports the proton to the neutron target. The 3NBT itself is 300m long, though during the initial beam commissioning of the RCS, the protons are dumped to the 4kW beam dump which is located at 40m apart from the RCS extraction. The other is the 3-50BT and it brings the beam to the MR injection about 240m. It has two vertical bending magnets, because the beam horizontal plane of the RCS and MR are different in 4.3m.

In order to keep the low beam loss at high intensity, large aperture vacuum chambers are used. It causes low sensitivity of some monitors. Radiation hardness is also required. On the other hand, low intensity (~1% of the full beam) operation is required for a commissioning. Large dynamic range is necessary for the system. It is described various instruments at J-PARC synchrotrons.

BEAM MONITOR LOCATION

The number of various instruments is summarized at Table 1. The beam position monitors (BPM) of the both rings are placed at almost every quadrupole magnet (QM). Some special BPMs are prepared for dedicated purposes. There are also some BPMs at the beam transport line. In the initial design, there were more destructive monitors, like MWPM (Multi-wire profile monitor), but we replace them and add the non-destructive one, like BPM. Because MWPM is destructive, it would be used only with low intensity not at high intensity operation.

The beam loss monitor (BLM) is important to keep low radio activity of the machines. Three different types of BLM, various time resolution and long term stability, are placed around the ring. DCCT and SCT are beam current monitors and MCT is used to observe multi-turn injection. FCT and WCM are bunch monitors, and some of them are used for RF control signal.

Some instruments, which are installed at the RCS injection or H0 dump line and slow/fast extraction line of the MR, are included in the table of the RCS/MR.

Table 1: Summary of the beam diagnostic system. For 3NBT, the number of counts is up to 4kW beam dump, not entire beam transport line. () indicates the number of instruments at Day-1.

Monitor	**RCS**	**MR**	**3NBT**	**3-50BT**
BPM (COD)	54	186		
for RF	3	4		
single pass	2+2	2+4	5	14
for ν-meter	1			
DCCT/SCT	1/1	2/0		
MCT	1			
FCT/WCM	2/2	3/1		5
for RF	2/1	3/2		
Exciter	2	2		
IPM	2	2(1)		
MWPM	7	3	2	9 (3)
Flying Wire		2(1)		
BLM	90/24/ 20	>300		

BEAM POSITION MONITOR

The ring BPM measures not only the closed orbit, but also one-pass position. It aims ±0.2mm position accuracy for the RCS and 0.1mm for the MR. The precise measurement is required to minimize COD (closed orbit distortion) and prevent the beam losses. In order to achieve above accuracy, beam based alignment is required. Although the MR has individual QM current control, the RCS does not. Since then, new scheme is considered [2].

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BPM Sensor Head

Electrostatic pickup with diagonal-cut cylinder is adopted because of its linear response to the position. One BPM set consists of one horizontal and one vertical electrode pairs. The BPM is installed inside the steering magnet due to the limited space. In case of the RCS, the electrode pairs are rotated with 45 degree to prevent interference between the BPM connector and the steering magnet. The BPM inner diameter is ϕ257, 297 or 377 for the RCS, and ϕ130, 134, 165 or 250 (enlarged from 200) for the MR. Their length is 360mm including a hydroformed Ti-bellows (QM ceramic duct side) for the RCS and 330mm for the MR [3,4,5].

The RCS BPM is made of titanium, which is lighter material and low residual radio activity. The surface processing to get good vacuum is simpler comparing to stainless steel. The RCS steering magnet generates 25Hz-oscillating magnetic field with maximum 450Gauss. In order to reduce eddy current loss, the sensor head has to be thin (1.5mm) with multi-rib shape to keep enough strength against pressure. To obtain lower cut-off frequency (<400kHz), the impedance matching transformer is placed close to the head.

The MR electrodes and chamber are made of stainless steel, SUS316L and the SMA coaxial vacuum feed through is made of SUS316L brazed with alumina ceramics. The electrodes are supported and insulated with small ceramic block positioned in grooves of the inner surface of the chamber. The coupling impedance is very small. The electrode capacitance is ~210pF.

In the RCS, there are 54 sensor heads over the ring with every half-cell. Exceptionally, two of them are bigger to meet large aperture in the injection area. For radial feedback for RF, three additional heads are prepared and placed at large dispersion section. Two out of three will be used in order to avoid possible COD effect.

The diameter for the 3NBT BPM is 282mm. The former is stripline type and the later is electrostatic type pickup.

BPM signal processing unit

The BPM signal processing unit is developed differently for the RCS and the MR. That of the RCS is based on VME, and that of the MR is separate box type. Both units have a similar feature, but differ at digital processing part due to their time structure. They are equipped with 4-input analog circuit, four 14-bit 40MSPS ADC (80MSPS for the MR). The analog circuit has RF transformer in the front for isolation, it has a reference path to calibrate the circuit. It has also step attenuators -30, -20, -10 dB and variable gain amplifier x1, x2, x5, x10 or their combination. Low pass filter of 5MHz (10MHz for the MR) can be selected.

Three alternative processing is possible: COD measurement, one pass position measurement and waveform measurement. In the COD measurement mode, it takes 1k, 2k or 4k (1k fixed for the MR) samples and performs FFT and searches a peak near n^{th} harmonic of the revolution frequency. The detected peaks from pair electrodes are used to determine the beam position which is proportional to difference and sigma ratio, Σ/Δ. Above procedure are repeated every 1ms, namely 20 beam positions are determined for each RCS acceleration cycle. In case of the MR, the default measurement period is 10ms.

The digital processing core is different, DSP for the RCS and FPGA for the MR. Since the beam absent period of the RCS is only 20ms, the shared memory is used to transfer data. On the other hand, the MR data is transferred through the LAN during longer break period. One pass position is detected with scanning peak and bottom of the digitised signal in time domain, then calculating Σ/Δ at every bunch and turn-by-turn to determine the position.

The MR pickup and its signal processing circuit was tested at KEK-12 GeV PS with beam intensity $4x10^{11}$ protons. If the BPM signal is too small during the commissioning period, additional pre-amplifier may be used at the close to the pickup.

324MHz-BPM

This BPM for the RCS detects 324-MHz or its higher harmonics components which are harmonics of Linac RF frequency in order to monitor painting process. The beam is injected continuously over 500 μs by multi-turn process and normal BPM sees only weighted charge distribution. Since the bunch structure of the Linac disappears quickly, detecting this frequency could distinguish the most recently injected beam from already circulated beam. The experiment was performed at KEK-Booster and it seems promising [6]. There are two of them within about $\pi/2$ phase apart, and their position information reconstructs the phase space parameters at the injection point.

At early beam commissioning, un-accelerated beam may be transferred to the 3NBT dump. To be more sensitive, the 3NBT BPM is designed to detect also the Linac frequency component.

There are also stripline type BPMs in the RCS injection line (L3BT), where is upstream of the injection septum magnets.

COHERENT TUNE MONITOR SYSTEM

The system consists of an exciter and an individual BPM similar to that of KEK-PS [7]. The exciter has a pair of stripline electrode and gives either horizontal or vertical transverse kick to the beam. Using white noise with limited bandwidth, only resonated frequency power excites the beam. One does not need to scan the frequency. Signal from an arbitrary signal generator is amplified by a 1kW (2kW for the MR) amplifier and transferred to the power divider near the exciter. The opposite phase signals are fed to the two electrodes from the down- to the upstream of the beam, otherwise the kick by the electric force and magnetic force do cancel out.

The signal from BPM is fed to a real-time spectrum analyzer [8] and betatron sidebands appear around the harmonics of the revolution frequency. The signal strength is expected to be –60dBm at full intensity, but two order of the magnitude lower operation is planed. In that case, data averaging operation might be necessary.

BEAM PROFILE MONITOR

Multi-wire profile monitor

There are seven multi-wire profile monitors (MWPM) around the RCS injection area to monitor the injection line or optimize H0 dump line. They are originally designed as 1mm pitch wire spacing, but it turns out that even finer spatial resolution is necessary. The design is modified that the wire pitch is enlarged 3 and 10 mm for both horizontal and vertical plane, but they are tilted with 17.7 degree with respect to the moving direction. The oblique wire arrangement and scanning method give better resolution.

One concern is that they might behave differently for H^- beam or H^+ beam. Especially, 5th MWPM, which is right after the charge exchange foil, has both beam modes depends on the foil inserted into or not. From the Linac wire scanner experience, bipolar bias may help [9].

For the 3-50BT and the MR injection/extraction/arbort line, MWPM are also installed. Survival under the high intensity proton beam and low beam loss are big issue. Several target materials has been irradiated by proton beams and ion beams to confirm radiation hardness. Among aluminium coated polypropylene, aluminium and carbon, thin carbon foil is promising. The efficiency of secondary electron emission was ~ 1-2%. The estimated beam loss is a few W at the design intensity. Utility should be carefully arranged, e.g. restricting the number of beam pulses.

Ionization Profile Monitor

An ionization profile monitor (IPM) is using residual gas ionization by the circulated proton. For the RCS design, it consists of three multi channel plates (MCP), electrodes for electric static field and a wiggler type magnet. Ionized electrons moved to the MCP along the electric field [10]. The required electric field gradient is above 1kV/cm against space charge and the vacuum chamber diameter must be larger than 300mm, then the bias power supply is selected to be more than 40kV. The magnetic field is static 500 Gauss to obtain 0.4mm of electron gyro radius. The field is parallel to the electric field and it suppresses defocus of the electron. The field homogeneity of less than 0.1% within active ±120mm area is obtained by 3D simulation. The correction poles are placed up-, down stream of the main pole for compensation. The stray BL product is $3x10^{-3}$ Tm along the beam pass. Each MCP is size of 80mm x 30mm and central one has 32ch and others have 8ch, mainly used to detect halo. There are two of them, for horizontal and vertical measurements, at high dispersion section. In future third IPM is foreseen at dispersion free section.

The IPM prototype has been built and tested at KEK-PS [11]. Both modes, electron collection mode and ion collection mode, have been performed with varying the magnetic field and electric field. With the electron collection mode, large secondary emission electron background was observed, but the beam size estimation seems to be consistent. In the ion collection mode, it is seen very clear signal, but measured profile seems to be broadening. We would use this experimental results and experience to the RCS and MR apparatus design.

Quadrupole monitor

Non-destructive fast response measurement of quadrupole moment of the beam in transverse plane is under development, using pickups with four electrostatic electrodes. At the KEK-PS beam, average quadrupole moment and then average beam emittance was obtained. Turn-by-turn measurement is the next subject [12].

Flying wire profile monitor

At the initial commissioning the flying wire profile monitor which will be similar to the one at the KEK-PS will be used with small intensity [13].

SUMMARY

Accelerator commissioning is planed to start in 2007. Various instruments of the beam diagnostic systems are carefully designed and being tested to achieve the successful commissioning and power increase after operation of the J-PARC RCS and MR.

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