DEVELOPMENT OF THE BEAM DIAGNOSTICS SYSTEM FOR THE J-PARC RAPID-CYCLING SYNCHROTRON

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Abstract

Development of the beam diagnostics system for the J-PARC Rapid-Cycling Synchrotron is described. The system consists of Beam Position Monitor (BPM), Beam Loss Monitor (BLM), Current monitors (DCCT, SCT, MCT, FCT, WCM), Tune monitor system, 324MHz-BPM, Profile monitors, and Halo monitor. The BPM is electro-static type and its electronics is designed for both COD and turn-by-turn measurements. Five current monitors have different time constants in order to cover wide frequency range. The tune monitor is consisted of the exciter and the beam pick-up electrode. For the continuous injected beam monitoring, 324MHz-BPM detects Linac frequency. Two types of profile monitor are multi-wire for low intensity tuning and the residual gas ionization monitor for non-destructive measurement.

INTRODUCTION

A rapid-cycling synchrotron (RCS) of the J-PARC (Japan Proton Accelerator Research Complex) provides large proton beam to a 1MW neutron target with 25Hz repetition. It is also used as an injector of 50GeV Main Ring synchrotron. The circumference of RCS is 348m. The proton is injected at 400MeV (or 181MeV) into two RF buckets and fast extracted at 3GeV [1]. The revolution frequency varies from 614 (469) to 836kHz. The beam intensity is 8.3×10^{13} with 400MeV (below 5.0×10^{13} with lower injection energy) and its circulating current reaches 11.1 A. In order to keep large aperture, big standard vacuum chambers are designed as inner diameter of 257, 297, or 377 mm. The sensor heads have to be as same as these chambers. 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.

BEAM POSITION MONITOR

The beam position monitor (BPM) system consists of a sensor head, signal cables and a signal processing unit. It is aimed to be ±0.2mm position accuracy, because the simulation implies that COD of less than 1mm requires accuracy better than 0.3mm.

The head is located at "main tunnel", second basement floor, and PEEK radiation hard cables are brought to "sub-tunnel" (lower radiation area) under "main tunnel". They are reconnected to four 8D coaxial cables with additional shield, and the signal is transported more than 100m to 1st floor where the signal processing unit is placed.

BPM Sensor Head

The BPM sensor head is an electro-static type and there are three diameter sizes according to the vacuum chamber. It has four electrodes with diagonal cut shape, in order to have a good linear response. The head 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. Because of extremely limited space, the head is only 360mm long including a hydroformed Ti-bellows for a ceramic duct side and installed inside a steering magnet, which generates 25Hz-oscillating magnetic field with maximum 450Gauss. In order to reduce eddy current loss, the head has to be thin (1.5mm) with multi-rib shape to keep enough strength against pressure. The electrode inside the vacuum is made of Ti-alloy (Ti-6Al-4V) whose conductivity is smaller to reduce eddy current. The gap between electrode and chamber is 2mm and length is 100mm. The ϕ257 head has capacitance of 230pF (plus 100pF of the cable up to transformer). Signal pick-up connectors are rotated with 45 degree for some space inside the steering magnet. Conversion to the X-Y coordinates has to be done at signal processing stage. To obtain lower cut-off frequency (<400kHz), the impedance matching transformer is placed close to the head.

The first ϕ257 prototype of above concepts was made and tested with the prototype steering magnet. Because only small power supply was available, a quarter of the field with twice faster rate (50Hz) was chosen to be comparable of eddy current loss. Temperature rise of the electrode was not significant. Using obtained effective heat conducting coefficient, joule loss at support plate is estimated. It turns out that it needs to be reduced for the ϕ377 head. Deformation occurs by clamping flange, heat or pressure difference. But the change of the electric capacitance is small (~0.3pF) and it does not affect for position determination.

The prototype was also performed the bench calibration. An aluminium antenna of ϕ30 mm and copper wire (ϕ0.4 mm) were used for comparison. The former needs to be corrected, since the mechanical centre and electric centre are slightly different. By wire method, mapping difference becomes smaller than ±0.2mm over ±100mm range.

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

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dispersion section. Two out of three will be used in order to avoid possible COD effect.

BPM Signal Processing Unit

The signal processing unit is designed as a 3-width VME module equipped with 4-input, analogue circuit, four 14-bit 40MSPS ADCs and one 600MHz DSP. One sensor head corresponds to one unit. The analogue 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 can be selected. Factor 5 variation of the peak current during 20ms and 10^{-3} resolution require 14bit. The shortest bunch length of 100ns needs 40MHz sampling. All these reasons and owing to lower power consumption, AD9244 is finally selected. A good clock generator is important, because its time jitter may degrade effective ADC bit.

The unit has three operational modes. In the COD measurement mode, it takes 1k, 2k or 4k 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. Above procedure are repeated every 1ms, namely 20 beam position will be determined for each acceleration cycle. Another is single pass mode. It compares the turn-by-turn (up to about 15,000 turns) peak in time domain and determines the position. The last mode is to use the unit as just waveform recorder for off-line analysis. The data size is as large as 1.6MB/ch.

During the COD mode, fast data transfer would be performed by the shared memory. But the noise from the backplane bus is an issue to be addressed.

A conceptual test was performed at KEK in the past, with an analogue prototype circuit and PCI based ADC [2]. Now prototype design is finished and its test is planed next month.

BEAM LOSS MONITOR

The beam loss monitor (BLM) is an important device to minimize the beam loss. There are three types of the BLM in the RCS [3]. One is scintillation monitor with a photo-multiplier (S-BLM). Another is a proportional chamber, Ar-CO2 (1%) gas filled (P-BLM). The last one is air ionization chamber modified from a coaxial cable whose inner conductor is supported by spiral polyethylene insulator (AIC-BLM) [4].

S-BLM will be used at injection or extraction areas because of its good time resolution. The P-BLM will be distributed every quadrupole magnet and they are also installed at close to the H0 dump or somewhere hot places revealed after the operation start. AIC-BLM will be distributed along the ring. Although its response is slow (~1msec), it is maintenance free and would be used to calibrate other two types of BLM owing to its stable characteristics.

BEAM CURRENT MONITORS

There are 10 current transformer (CT) of five different time constants. DCCT will be purchased from Bergoz [5]. Not only the DCCT, but other CTs have a big core (I.D. more than 380mm) to fit the middle size chamber. The frequency response is from DC to 10kHz and the full scale current ranges are 150mA, 1.5A and 15A. Slow CT (SCT) has a feedback amplifier to extend its time constant [6]. The outputs of these are circulating beam current and they increases as revolution period faster. Since it is more important to monitor the number of protons, the outputs are normalized by the velocity using RF frequency.

Medium CT (MCT) is designed to observe the injection process, which the beam current increases gradually within 500 µs. Its frequency response is from 1.6 Hz to 1.6 MHz at –3dB.

There are four Fast CTs (FCT), whose frequency response is up to 40MHz. Two of them are used for RF phase feedback. Three of Wall Current Monitors (WCM) will be used for RF feedforward control or bunch shape monitoring. The wall current goes through many resistors over the ceramic gap of the chamber and a troidal core inductance is loaded to make frequency cut-off lower. To reduce heating at shunt resistors, they would be small as 0.1 Ω with more than 100 of a few tens Ω resistors. The frequency response is from 1kHz to 500MHz.

High beam current may cause the magnetic core saturation and it makes the droop worse. But using smaller shunt resistance, one can recover the droop characteristics. Availability of such big size is also trouble. FINEMET® [7] FT-3M is now our selection.

COHERENT TUNE MONITOR SYSTEM

The system consists of an exciter and an individual BPM similar to that of KEK-12GeV PS [8]. 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 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 [9] 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 eight multi-wire profile monitors (MWPM) around the injection area to monitor the injection line or optimize H0 dump line. They have mostly 64 wires per plane with 1mm pitch. The wire is gold plated tungsten of 0.1mm diameter. Thinner (0.03mm) option is preserved in case of heat dissipation problem. MWPM1 has 48 wires and bigger MWPM7&8 have longer wire spacing 3 or 4mm. Three out of eight MWPM have both horizontal and vertical wire planes.

One concern is that they might behave differently for H^- beam or H^+ beam. Especially, MWPM6 has both beam modes depends on the charge exchange foil inserted into or not. From the Linac wire scanner experience, bipolar bias may help [10]. Because they are destructive monitor, they would be used only for commissioning or lower intensity mode with the particles single passage.

The injection bump magnets near the MWPM seem to be a serious noise source. Required charge sensitivity is quite high, though the preamplifier has to be placed at "sub-tunnel" with long cable. The various types have been studied, a charge sensitive or voltage sensitive, differential or single ended earth, and different shielding. A radiation hard stepping motor or a position resolver for long insertion (250mm) are also development items.

Ionization Profile Monitor

An ionization profile monitor (IPM) is using residual gas ionization by the circulated proton. 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 [11]. 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 $3\text{x}10^{-3}$ 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 prototype would be tested at KEK-PS soon.

OTHER MONITORS

324MHz-BPM

This BPM detects 324-MHz or its higher harmonics components which is Linac 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 [12]. There are two of them within about $\pi/2$ phase apart, and their position information reconstructs the phase space parameters at the injection point.

The higher harmonics disappear more quickly and it is favour for this purpose. However, the 3^{rd} harmonics is above cut-off frequency of the chamber. HOM damper might be necessary to suppress noise.

Halo Monitor

The halo monitor is placed at the extraction beam line which transports the protons to the neutron target. It has two aluminium plates, and they are inserted into the vacuum horizontally and vertically to interrupt the beam halo. Due to the electron secondary emission, some charge signal is expected from the plate.

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.

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