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STUDY OF BEAM INJECTION EFFICIENCY IN THE FIXED FIELD ALTERNATING GRADIENT SYNCHROTRON IN KURNS

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Abstract

In the fixed field alternating gradient synchrotron at our institute (KURNS), there are serious beam losses during beam injection. In order to evaluate the efficiencies of beam injection, rf capture, and beam extraction, separately, a well calibrated electrostatic bunch monitor was installed to measure the circulating beam current at each energy region. This paper reports the design of the monitor, calibration, and first results of beam measurement.

INTRODUCTION

Accelerator complex of fixed field alternating gradient (FFA) synchrotrons has been developed in Kyoto university integrated radiation and nuclear science (KURNS), aiming to demonstrate the basic feasibility study of accelerator driven sub-critical system (ADS). Originally the accelerator complex was composed of three cascade FFA rings [1] connected to sub-criticial reactor in Kyoto university critical assembly (KUCA). The ADS studies with this system were started in March 2009 [2].

In 2011, the injector was replaced by linac and H$^-$ ion beams of 50 µs long were injected directly to the final FFA ring with charge exchange multi-turn injection [3]. With this upgrade the accelerated beam intensity has been increased up to 1 nA in 20 Hz repetition, but this number is only 0.25% of the H$^-$ beam from the linac.

A number of studies, mainly based on simulation, has been done to explain how beam was lost [4]. However, the beam loss ratio which is reproduced in the simulations were 3% at the worst case. In order to investigate the beam loss, it is necessary to measure circulating beam current at each time. We installed a well calibrated nondestructive beam monitor, which can measure the beam current independent of transverse distributions. This paper reports the design of the monitor, calibration, and first results of beam measurement.

ACCELERATOR IN KURNS

FFA Synchrotron Ring

The KURNS FFA synchrotron accelerates proton beams of 11 MeV up to 100 MeV or 150 MeV. This machine is so called *radial sector scaling FFA*, at which the main magnets are designed such that the field $B(r)$ along a radius is proportional to r^k. Dispersion function is therefore $(k+1)r$, where r is the closed orbit radius. Having k=7.6, the orbit excursion during acceleration is 74 cm in the ring.

Transverse emittance of an injected beam is assumed to be 5 πmm-mrad in both horizontal and vertical phase spaces, which corresponds to 20 mm in real space.

Table 1: Parameters of FFA Main Ring and Injector

Parameter	Value
Particle	Proton
Kinetic energy	11 – 150 MeV
Revolution frequency	1.558 – 3.85 MHz , h=1
Average orbit radius	4.58 – 5.32 m
Dispersion	24 mm/MeV
Acceleration speed	1.4 keV/turn

Injected beams are captured and accelerated by a moving rf bucket. In ordinary operation, the rf amplitude is fixed at 4 kV and the accelerating phase is 20 deg over the acceleration. Thus the energy gain is 1.4 keV/turn and the orbit shift by the acceleration corresponds to 1 mm/30 turns. Since no bump orbit system is employed here, it is assumed that the injected particles hit the foil for more than 100 turns until its orbit goes out of the foil. It causes energy losses and emittance growths and a part of the beam is lost.

Conventional Monitors, BPM

The circulating beam current is used to be measured non-destructively by two electro-static bunch monitors. One is a single flat electrode covering only the bottom half of the chamber, aiming to detect the vertical oscillation, and the other is composed of an array of five triangular electrodes for horizontal oscillation, respectively. The output from those monitors depends on the transverse coherent motions. Moreover, because the opening angles of them seen by a beam is not enough, the sensitivity might be reduced around both edges (highest and lowest energy orbit). In order to evaluate precisely the beam loss from injection to extraction, a bunch monitor dedicated to the beam intensity monitors are necessary.

FULL APERTURE BUNCH MONITOR

We have developed an electrostatic pickup (FAB) which has a wider aperture than the full range of orbit excursion, with surrounding it (Fig. 1). The monitor was installed at the straight section across the trajectory of injected H$^-$ beams, as shown in Fig. 2. The charge density of injected H$^-$ beams are measured as well as that of circulating beams with the same pickup efficiency.

Gap distance between vacuum chamber and the lower plate is 20 mm and the capacitance is estimated to be 300 pF, including readout structure and head amplifier.

Equivalent circuit of a electrostatic pickup is shown in Fig. 3, where C_m and R are the capacitance and resistance

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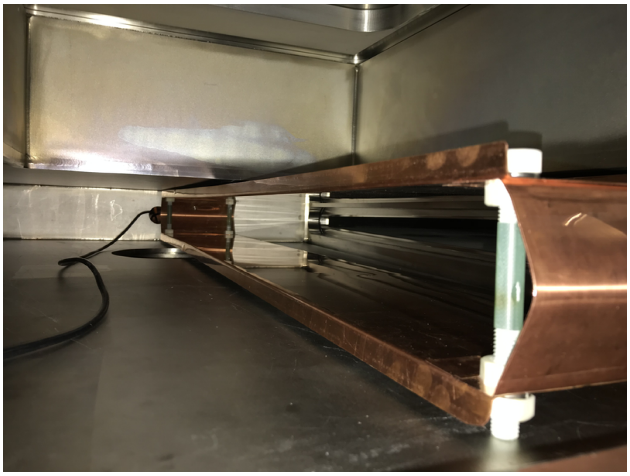

Figure 1: Photo of full-aperture bunch monitor. 100 mm(W)×75 mm(H)×158 mm(L).

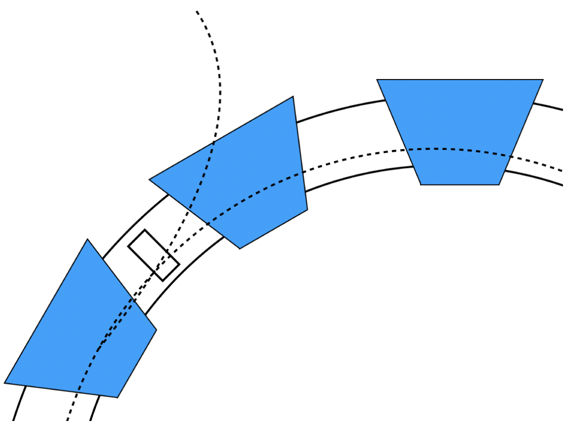

Figure 2: Location to install a new bunch monitor (rectangle symbol). Dashed lines show the trajectory of injected H^- beam and circulating orbit at injection energy.

of the monitor, C_b the capacitance between the beam and the monitor, and Q_b the charge of the bean seen by the monitor, which is proportional to the peak beam current I_p as $Q_b = (\ell/v)I_p$. When a part of the beam hits the monitor, the effect is modeled by an external current source I_g. The output voltage is then,

$$V(t) = \frac{e^{-t/\tau}}{C_m} \int \left(I_g(t) + \frac{\mathrm{d}Q_b(t)}{\mathrm{d}t} \right) e^{t/\tau}\, \mathrm{d}t\ . \qquad (1)$$

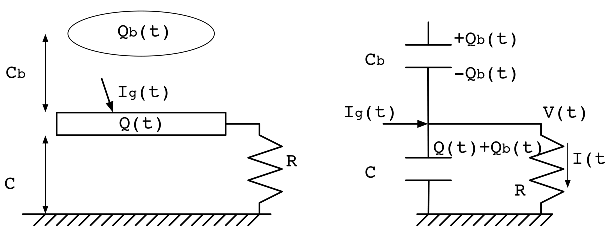

Figure 3: Equivalent circuit.

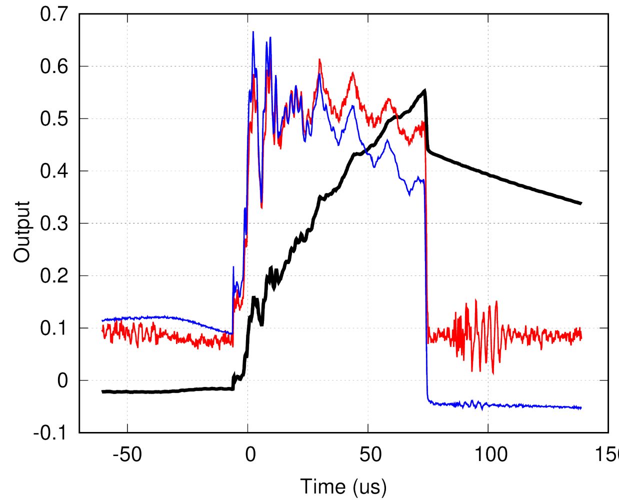

Figure 4: Output from full-aperture bunch monitor (black, in 0.1 V/div), destructive beam current monitor (red, -0.5 mV/div), and current transformer (blue, -5 mV/div).

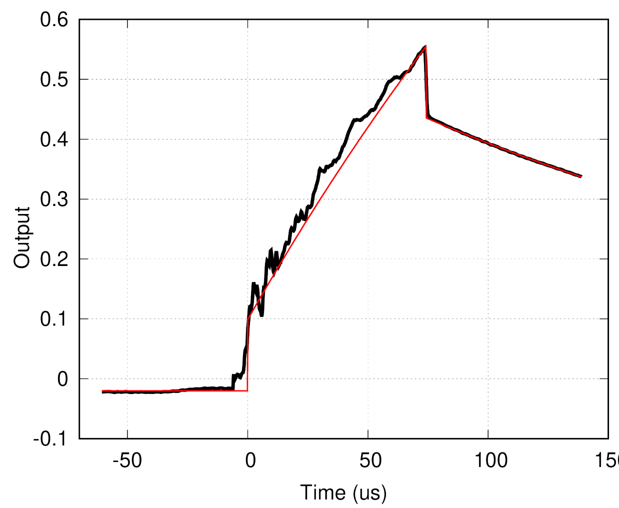

Figure 5: Best fit function (red) for full-aperture bunch monitor output waveform (black) in Fig. 4, based on the assumption of rectangular input.

C_m is assumed 300 pF, including feedthrough and head amplifier.

Calibration with a Test Beam

In order to calibrate the FAB, a long pulse of test H^- beam was injected to the main ring. The beam was measured by three different monitors; FAB, current transformer (CT) right before the injection, and destructive beam current monitor (FC) which was installed behind the FAB, respectively. Here the FC measured 68 nA in 20 Hz injection rate, which corresponds to 2.1×10^{10} particles/pulse. The voltage output from the FC showed a rectangular pulse with 74 µs duration, while CT had a capacitive time constants, respectively (Fig. 4).

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Assuming that Q_b and I_g are constant during the pulse, the response of the FAB is

$$V(t) = RG\times\begin{cases} I_g - \left(I_g - \frac{Q_b}{\tau}\right)\exp\left(-\frac{t}{\tau}\right) & (0 < t < T) \\ \left(e^{T/\tau} - 1\right)\left(I_g - \frac{Q_b}{\tau}\right)\exp\left(-\frac{t}{\tau}\right) & (T < t) \end{cases}$$

plus the background V_{bg}, where G=200 is the voltage gain of the amplifier. This function reproduced the measured waveform as Fig. 5 with best fit parameters of τ = 265 μs, the instantaneous current $I_p = (v/\ell)Q_b$ = 45 μA, and I_g = 10 nA, respectively. The fitting time constant was consistent with the expected value of 300 pF×1 MΩ. Also, the peak current is consistent with that measured by FC.

The time constant is much longer than the rf period, so that the deformation of a bunched beam shape is expected to be negligible. In addition, the beam loss current which hits the monitor, I_g, is negligible compared to I_p. Therefore, the instantaneous current of a bunched beam is measured as

$$I_p = 2.6\,(mA/V)\cdot\frac{v}{c}V$$

where v/c is the beam velocity.

First Measurement of an Accelerated Beam

An accelerated beam was measured with FAB (Fig. 6), after removing the FC. A periodic spikes of noise are seen at the FAB output, which needs to be compensated. The number of circulating particles is proportional to the output voltage integrated over an rf cycle,

$$\begin{aligned}\tilde{I} &= f_{rep}\times\int I_p\,dt \\ &= 50.32(nA/Vs)\times\frac{v}{c}\times\int_{rf-cycle} V\,dt\end{aligned}$$

where repetition rate is f_{rev} = 20 Hz. Obvious rapid beam losses are seen at 3 ms and 17 ms after the injection.

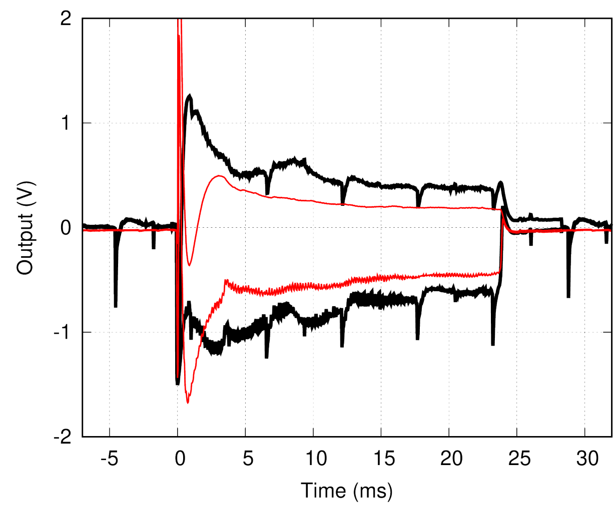

Figure 6: Envelope of the FAB output (black) and normal BMON (red).

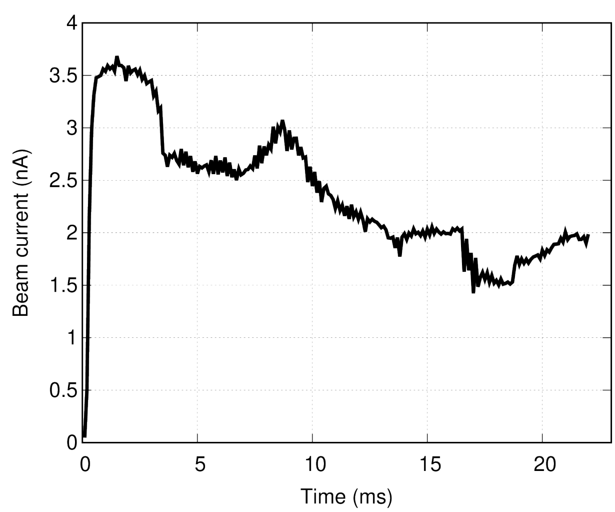

Figure 7: Normalized FAB output waveform, showing the circulating beam current.

CONCLUSION

An electrostatic bunch monitor, having a very wide aperture has been installed in our FFA accelerator. Beam intensity is measured with this monitor throughout the acceleration. Beam studies with the monitor to improve the injection and acceleration efficiency is starting

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