STUDY OF INTEGER BETATRON RESONANCE CROSSING IN SCALING FFAG ACCELERATOR

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Abstract

Fast crossing of integer betatron resonance has been examined in a scaling Fixed Field Alternating Gradient (FFAG) accelerator in KURRI (Kyoto University Research Reactor Institute). By virtue of fast acceleration, large horizontal and momentum acceptance, the FFAG accelerator has enough capability of betatron resonance crossing. The amplitude of the coherent betatron oscillations was measured during the resonance crossing, with different crossing speed and harmonic field. The results were compared with tracking simulations.

INTRODUCTION

To avoid serious beam losses and blow-ups, the betatron tunes of circular accelerators are usually kept away from resonance conditions. In a scaling type of FFAG accelerator, the scaling law $B(r) \propto r^k$ provides constant betatron tunes for all energies. In a non-scaling FFAG, the betatron tunes change during acceleration [1]. However, resonance crossing is expected to be not so serious when the tune variation is fast enough, since the tunes stay in resonant condition only for a short time. To verify this prediction, experimental studies have been performed on half integer resonance [2] and third integer resonance [3] crossing. In both cases, the beam loss caused by betatron resonance was limited when the crossing speed was high ENOUGH. However, there were so far no experimental evidence for integer resonance.

Baartman investigated the dynamic resonance crossing[4] and derived analytically the amplitude growth as a function of crossing speed, harmonic field strength and so on. In case of integer resonance, the amplitude growth is proportional to $\tilde{B}/\sqrt{\nu'}$, where $\tilde{B}$ is the harmonic field and ν' the resonance crossing speed.

Table 1: Experimental conditions of Injector

Magnets	8 spiral sector magnets
Acceleration	Induction, ≤3.5 kV/turn
Orbit radius	0.60∼0.99 m
Beam energy	0.12∼0.30 MeV
Horizontal tune	1.1∼0.9 (See Fig.2)

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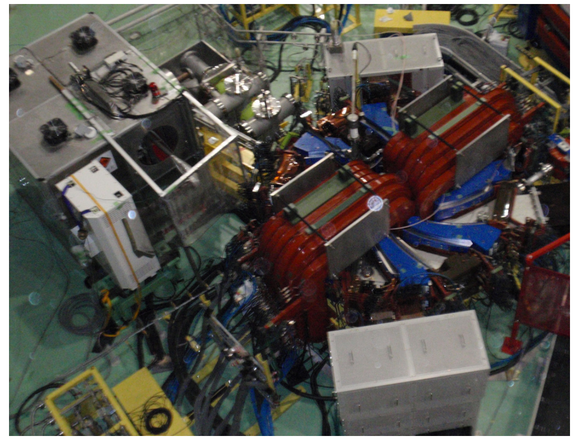

Figure 1: Injector FFAG.

In this paper, the integer resonance crossing experiments have been done with the injector of the FFAG accelerator complex [5] built in Kyoto University Research Reactor Institute (Fig. 1). The resonance of $\nu_x = 1$ was artificially crossed with different (1)crossing speed and (2)harmonic field. Coherent betatron oscillation was observed during the resonance crossing, and the amplitude growth was compared with simulations.

EXPERIMENTAL SETUP

The “injector” is a scaling type of FFAG accelerator with induction acceleration with 8 spiral sector magnets. Maximum output energy of a proton beam is 2.5 MeV. The field index k can be varied by means of 32 trim-coils to realize variable output energy. Without exciting trim-coils k is zero within the imperfection of the magnet design, and the horizontal tune stays in the neighborhood of 1. Figure 2 shows the simulated betatron tunes based on the field calculation by TOSCA code. In this figure, the averaged closed-orbit radius is shown as the horizontal axis, instead of beam energy. During acceleration, the integer resonance of $\nu_x = 1$ is crossed at $R = 765$ mm, where

$$E = 195\ \mathrm{keV} \quad \text{and} \quad \frac{d\nu}{dE} = -0.0024\ /\mathrm{keV}. \quad (1)$$

Resonance crossing speed could be controlled by changing the accelerating voltage. The maximum accelerating voltage is 3.5 kV/turn.

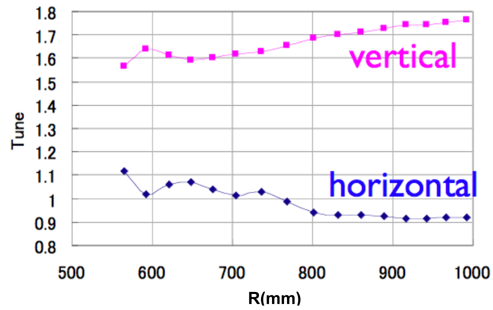

Figure 2: Tune variation with accelerator radius

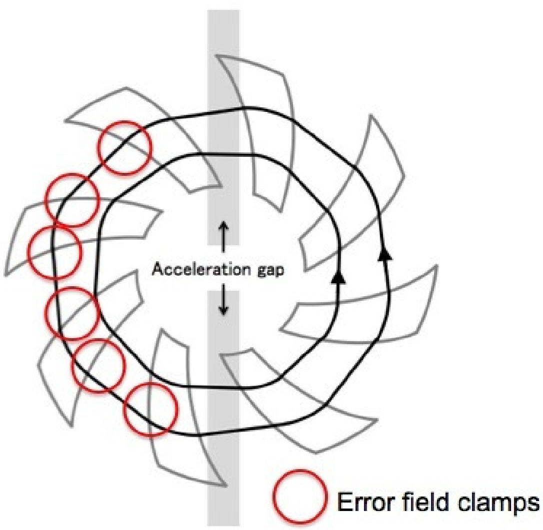

Figure 3: Distribution of error-field clamp: The gap of field-clamps checked with open circles were 10 mm wider than the others.

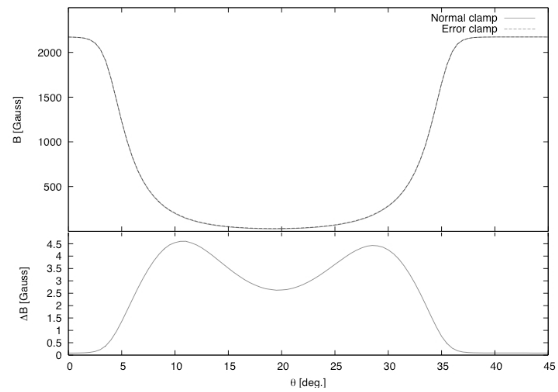

Figure 4: Comparison of the magnetic field.

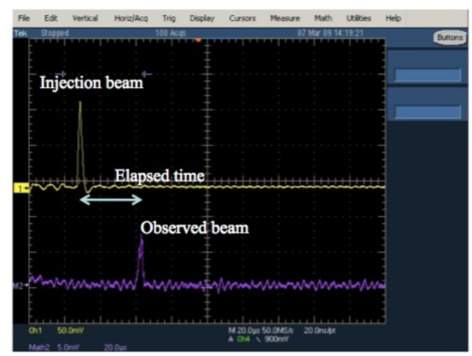

Figure 5: Beam measurement using a radial probe: Top signal is the beam at ion source. Bottom signal is the beam observed with the radial probe.

Driving force of the integer resonance was produced by “error sector magnets”, where field-clamp gap was enlarged. The differential field was 4.5 Gauss at its maximum, as shown in Fig. 4. The error sectors were distributed over one half of the accelerator rings (See Fig. 3), so that the first harmonic component was excited.

The injected beam was measured by a current transformer (CT). The beam was chopped into 5 μs pulses, which corresponds to about five revolution periods. The beam current in the injector was measured with a Faraday cup, which can be moved radially. The dimensions of the Faraday cup are 15 mm (H)$\times$10 mm(V).

EXPERIMENT

The coherent betatron oscillations were measured as follows. The accelerated beam was measured by the radial probe, and the time delay (T) from the ion source was measured as shown in Fig. 5 for different probe positions (R). The function $R(T)$ shows the coherent oscillations. It is worth noting that only increasing parts of $R(T)$ can be observed with this method.

Experiments were done with acceleration voltage of 0.9 kV/turn and 3.5 kV/turn, respectively. In Figs. 6 and 7, the closed circles show the experimental results. The stepping structures were observed in the figures, as expected. The measured coherent oscillation was compared with Runge-Kutta simulations in TOSCA field map, shown as the solid line in the figures. Since the initial amplitude and phase were unknown, the most fitting values were chosen here. The simulated coherent oscillation agreed with the measured ones in both cases with the common initial conditions. There were coherent oscillation with the amplitude of 10$\sim$20 mm at the initial conditions. The amplitude became larger around $R = 765$ mm, and then the growth was stopped after $R \sim 800$ mm. Thus, it is verified that the amplitude growth is limited when the tune variation is fast enough.

The final amplitude was estimated to $\sim$80 mm in both cases. Comparing two experimental results with different crossing speed, no difference of the amplitude growth was observed. The reason is related to the initial coherent oscillations. The amplitude growth gets maximum when the initial oscillation is on-phase with the driving force, while it gets minimum when they are out of phases. In the experiment with the acceleration voltage of 0.9 kV/turn, the initial oscillation are out of phase (See the curve in Fig. 7 around $R \sim 750$ mm). Therefore the amplitude growth was smaller than that of expected [4].

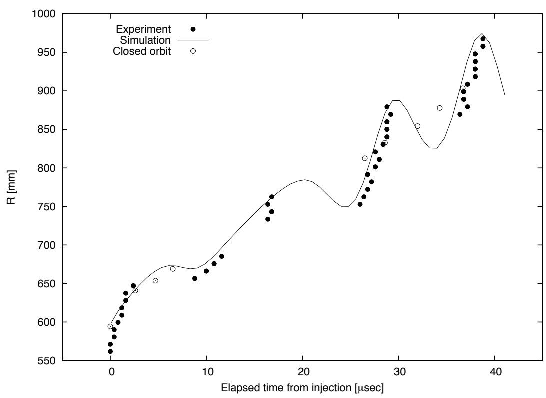

Figure 6: Result of beam measurement with an acceleration speed of 3.5 kV/turn. Closed circles and open circles stand for the experimental result and closed orbit derived from beam tracking simulation, respectively. Results of tracking simulation is presented with the solid line.

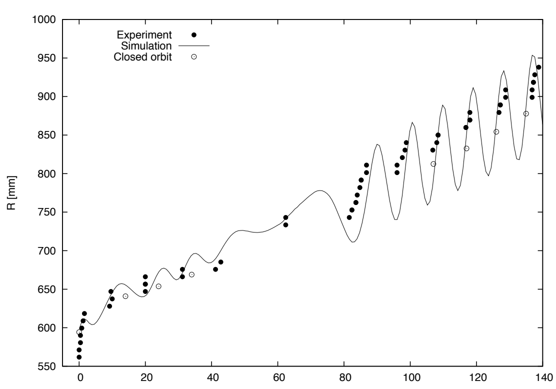

Figure 7: Similar to Fig. 6 with slower acceleration speed (0.9 kV/turn).

SUMMARY

Fast crossing of integer betatron resonance $\nu_x = 1$ has been examined in the injector of the KURRI FFAG complex. The beam survived after the resonance crossing, because of the fast tune variation and large horizontal acceptance. The measured coherent oscillation after the resonance crossing was reproduced by Runge-Kutta simulations. The simulated amplitude growth was proportional to $\nu'^{-1/2}$, which is predicted in Ref. [4].

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