DYNAMIC APERTURE OF THE POP-FFAG SYNCHROTRON

M.Yoshimoto*, T.Adachi, M.Aiba, S.Machida, Y.Mori,
A.Muto, R.Muramatsu, C.Ohmori, I.Sakai, Y.Sato, M.Sugaya, A.Takagi,
R.Ueno, A.Yamazaki, T.Yokoi, U.Yonemura, M.Yoshii, Y.Yuasa,KEK,Ibaraki, Japan
K.Koba, FNAL, Batavia

Abstract

Fixed Field Alternating Gradient (FFAG) synchrotron is able to have much larger acceptance than ordinary shynchrotron. It was ascertain experimentally that the Proof of Principle(PoP)-FFAG synchrotron has an acceptance more than 4000 π mm-mrad. However, when the tunes are set near the betatron resonace, the acceptance of FFAG decreases because the dynamic aperture becomes smaller than the physical aperture.

In order to investigate that dynamic aperture depends on the betatron resonance, the phase space trajectory and beam loss are measured varying the operation points in the PoP-FFAG.

1 INTRODUCTION

The PoP-FFAG is the world first proton FFAG synchrotron constructed in 2000. After the first proton acceleration, we have been carrying out the various beam dynamics studies. Through the studies of the PoP-FFAG, it became clear that the betatron tune is tunable varying F/D ratio [1] and the PoP-FFAG has large horizontal acceptance of more than 4000 π mm-mrad [2].

The horizontal acceptance dependes on the phase advance per one cell. Through the 1-demensional tracking simulation with hard edge model, some relation between the phase advance and the acceptance is found [3]. Figure 1 shows the relation between phase advance and the normalized acceptance. By introducing a normalized acceptance, the relation is valid for different machine parameter. Here normarized acceptance is defined as the acceptance devied by normalized factor, r_0/kN. From this result the beam acceptance decreases rapidly by setting the horizontal tune near the structure resonance (phase advance = 120°, 90°, 72°), because the dynamic aperture becomes smaller than the physical aperture.

In order to surveyed the dynamic aperture experimentally, the beam motion in the horizntal phase space is the measurement by varying the operation point. In usual experiments of the PoP-FFAG, the operation point is set so that the horizontal phase advance per one cell is about 100deg. Therefore, it is expected to have a large horizontal acceptance. By changing the F/D ratio, the operation point can be controled, that is the betatorn tune can be adjusted. In this peaper, by reconstracting the trajectory in the phase space and measuring the beam loss, the dynamic aperture of the PoP-FFAG was studied.

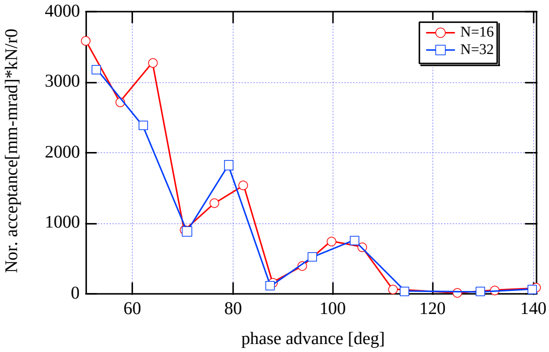

Figure 1: Normalized horizontal acceptances with different machine parameters, from the 1 dimensional tracking simulation with hard edge model. Horizontal phase advances are varied by changing the field index (k value).

2 THE METHOD OF THE PHASE SPACE TRAJECTORY

In the PoP-FFAG, the amplitude of the horizontal betatron oscillation can be controled by introducing the injection error. It is changed by varying bump high voltage. In the privious studies, the acceptance is estimated by the beam position observed with the single Beam Position Monitor (BPM) [2]. In such a case, the oscillation of the beam position can be measured, but the oscillation of the phase space can not be observed. In order to reconstract the transverse beam oscillation in the phase space, a new horizontal BPM is installed in the PoP-FFAG again, and it is located in the adjacent straight section of the old BPM. A phase advance between the BPMs is about 90 deg (see Figure 2).

The beam angle at the BPM is obtained by

$$x_1' = \frac{1}{sin\phi_{21}\sqrt{\beta_1\beta_2}}x_2 - \frac{(cot\phi_2 1 + \alpha_1)}{\beta_1}x_1 \qquad (1)$$

where ϕ_{21} is the betatron phase advance between two BPMs, and β_1, β_2 and α_1 are twiss parameters at two BPMs respectively. The phase advance can be estimated from the measured horizontal betatron tune. Twiss parameters are calculated from the tracking simulation. Figure 3 shows the typical result of the transverse betatron oscillation measured by the two BPMs, and the phase space trajectory reconstracted from the two betatron position.

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[*] myoshi@post.kek.jp

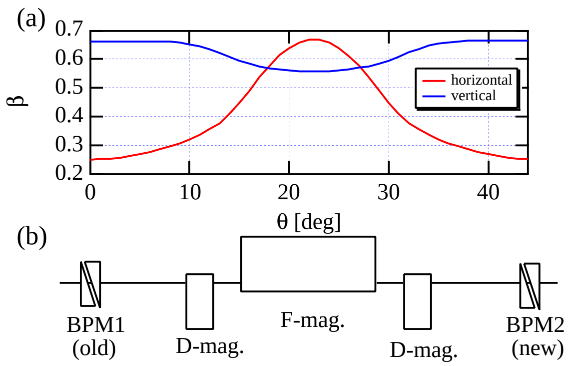

Figure 2: Location ot two BPMs. (a) Calculated horizontal and vertical beta function obtained by tracking simulation between 1 cell. (b) Location two BPMs and sector magnet.

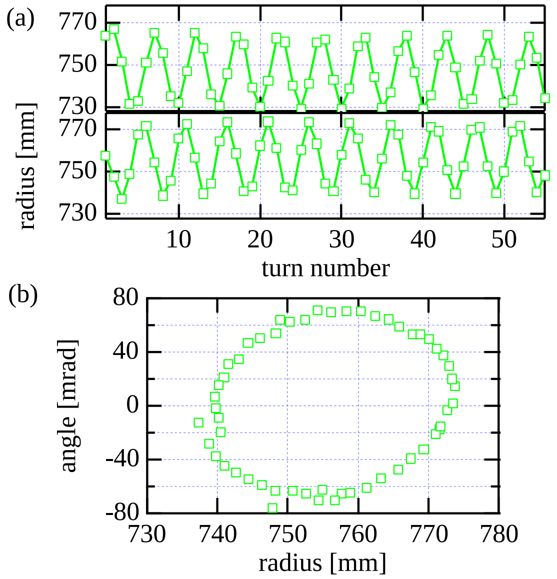

Figure 3: Typical reconstructing beam trajectory on the phase space. (a) Measured betatron coordinates at two horizontal BPMs vs the number of turn. (b) The measured betatron Poincare map of phase space reconstructed from (a).

3 THE BEAM MOTION AT THE RESONANCE CONDITIONS

In radial FFAG, the betatron tune can be controled varying the ratio of the focusing field (B_F) and defocusing field (B_D) which is called F/D ratio. In this paper, F/D ratio is defined as $\int B_F d\theta / \int B_D d\theta$ at the mean radius.

By changing the F/D ratio, the operaion point was controled and can be set around the betatron resonance. Figure 4 plots the observerd betatron tunes of the operation points used in the experiment. In usual experiments, operation point of F/D ratio=3.9 was employed.

In each operation point, by changing the amplitude of the betatron oscillation, the trajectory in the phase space and the beam loss was measured. The beam loss was obtained by integrating the BPM signals turn by turn, and normalized by the value of the first bunch BPM signal. Figure5 summarized the results.

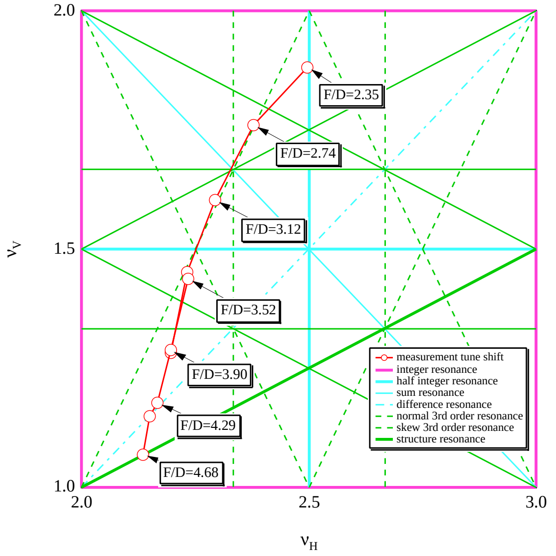

Figure 4: Betatron tune shift on the tune diagram varing the F/D ratio.

If the F/D ratio increases (Figure5 (e)→(g)→(g)), the central orbit shifts inward. Thus, the physical aperture gets smaller and acceptance is also reduced. In addtion, the point of F/D ratio=4.68 is around the normal sextupole resonance, so the beam vanished rapidly owing to the strong resonance.

As the F/D ratio gets smaller (Figure5 (e)→(d)→(c)→(b)→(a)), the central orbit shifts outward. In result, the physical aperture gets larger. However, according to the beam trajectory in the phase space, it was found that the observed acceptance gets reduced in actual. In addition, as the amplitude get larger, the tragectory in the phase space does not traces a simple ellipse and the phase space ellipse was smeared out. It would be explained with the follwing way; due to the non-linear coupling resonance, the dynamic aperture gets smaller than physical aperture. It results in drop of the horizontal acceptance.

This speculation can be supported from the results of the beam loss measurement. The beam loss rate in usual experiments (Figure5 (e)) can be explained by the charge transfer proccess with H_2 molicure in the ring [1]. In this study, the amplitude dependence of the beam loss is measured. In Figure 5 (e) and (f), beam loss does not change so much up to a certain amplitude and the loss increased rapidly beyound it. It means that the dominant beam loss occurs at the injection septum. On the other hand, For Figure 5(a),(b) and (c), as the amplitude gets larger , the beam loss also increases as well. In the case of the non-linear coupling resonance, the boundary of the dynamic aperture in the horizontal phase space was smeared out, so that the beam loses as the amplitude increases.

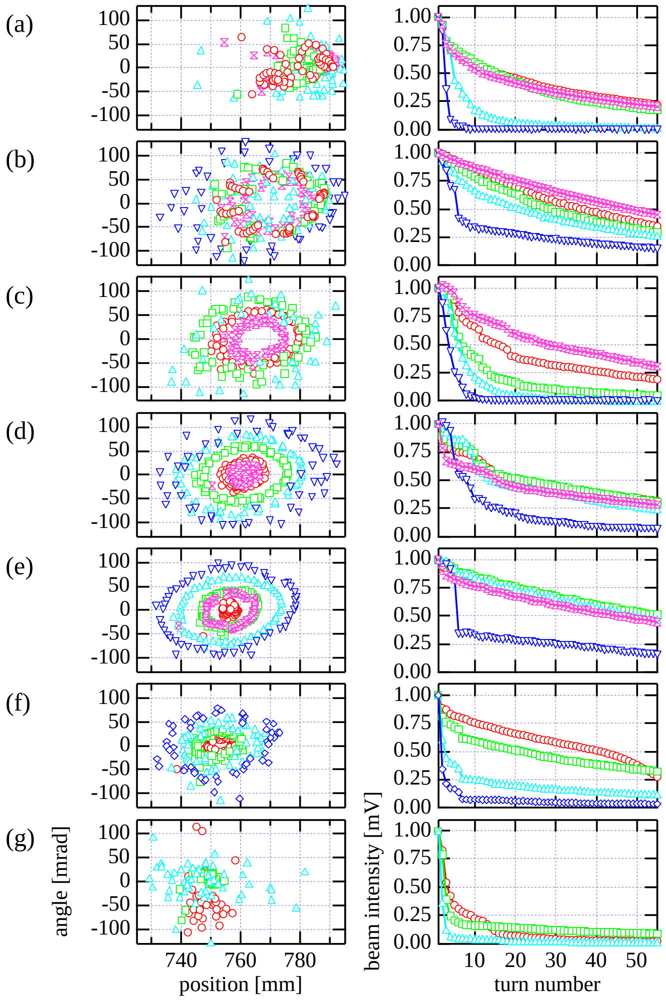

Figure 5: Measured Poincare map of the phase space and beam loss varying the amplitude of the betatron oscillation in the various F/D ratio, (a) 2.35 (b) 2.74 (c) 3.12 (d) 3.52 (e) 3.90 (f) 4.29 (g) 4.68 .

4 SUMMARY

The dynamic aperture is obserbed experimentally in the PoP-FFAG. It is found that by setting the betatron tune around the resonance line, acceptance gets smaller and phase space ellipse was smeared out. Moreover, the amplitude dependence of the beam loss is observed

REFERENCES

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