DEVELOPMENT OF A FFAG PROTON SYNCHROTRON

M. Aiba, K. Koba, S. Machida, Y. Mori, R. Muramatsu, C. Ohmori, I. Sakai, Y. Sato, A. Takagi, R. Ueno, T. Yokoi, M. Yoshimoto, Y. Yuasa, KEK, Ibaraki, Japan

Abstract

In order to investigate Fixed Field Alternating Gradient(FFAG) principle for high intensity proton synchrotron, a small POP(Proof Of Principle) FFAG which accelerates proton beams from 50keV to 500keV has been developed. Up to now, injection, beam storage and acceleration were successfully demonstrated, and show satisfactory agreement with calculation.

1 INTRODUCTION

Recently, high repetition accelerator is drawing attention from the various fields which require high intensity proton beam. FFAG synchrotron becomes a candidate of such an accelerator with the help of a high gradient and broad band cavity which was recently developed[1]. In addition, since the FFAG principle was proposed and a first electron model was tested[2][3][4][5], there was almost no activities for last thirty years . Therefore, we would like to re-establish FFAG from the more advanced accelerator view points and with the latest design tools such as 3D modeling of magnets and a sophisticated tracking code.

From the above motivation, a FFAG Proof of Principle synchrotron was designed and constructed at KEK. The POP FFAG, which is to accelerate proton beam from 50keV to 500keV, is a radial sector type FFAG with triplet focusing in one magnet piece. FFAG obtains its focusing through complicated 3-dimensional magnetic field. The difficulty to calculate such field was the bottleneck of FFAG design when FFAG was proposed. Thus, we carried out field measurement of the sector magnet and compared with the field calculated by 'TOSCA'¹. The discrepancy between measured and calculated field was found to be less than a few percent. The result supports our design strategy of FFAG relying on computational field. Then, through multi-particle tracking using calculated field map and Runge-Kutta method, the POP FFAG was designed.

The schematic view of the POP FFAG is shown in Fig. 1, and table 1 summarizes main design parameters.

2 ION SOURCE AND INJECTION

2.1 Ion source and beam transport

A H⁺ beam is produced in the multi-cusp type ion source. It is extracted with the width of $50\mu s$ and accelerated to 50keV by the extraction electrode. The applied voltage was tuned with the precision of 10V in order to take into account the beam loading effect.

Table 1: FFAG POP model parameters	
Type of magnet	Radial sector type(Triplet)
No. of sectors	8
Field index(k-value)	2.5
Energy	$50 \text{keV}(\text{injection}) \sim 500 \text{keV}$
Repetition rate	1kHz
Magnetic field	Focus-mag. : 0.14~0.32 Tesla
	Defocus-mag. :0.04~0.13 Tesla
Radii of closed orbit	$0.81 \sim 1.14 m$
Betatron tune	Horizontal : 2.17~2.22
	Vertical : 1.24~1.26
rf frequency	$0.61 \sim 1.38 \mathrm{MHz}$
rf voltage	1.3 ~ 3.0 kVp



Figure 2: Result of field measurement

As shown in Fig.3, the extracted H⁺ beam was chopped to the width of 500ns by a chopper electrode where pulsed voltage of 1.9kV was applied. The short-bunched beam allows us to monitor circulating beam, which turns around every $1.6\mu s$, and its transverse position.

The beam transport line goes through a chamber of the ring. The resultant long drift and bending due to the fringing field of the sector magnet require focusing elements and steering elements in both side of the intervening chamber. For focusing, the transport line has a triplet-quadrupole magnet and a pair of solenoid magnets. For vertical and horizontal steering, three pairs of steering magnets are installed there. The optimization of the beam transport line by tuning the steering magnets showed good agreement with calculation.

Injection 2.2

As traversing the septum, the beam is bent 90 degree and injected into the ring about 4cm inside of the closed orbit of

¹Shape of the sector magnet can be seen in [6]



Figure 1: Top view of POP FFAG



Figure 3: Chopped beam pulse observed at Faraday cup in the transport line (7-1 of Fig.1)

the injection energy. The septum consists of a pair of concentric electrodes. Negative high voltage(typically 20kV for 2cm aperture) is applied to the inner electrode. Outer electrode, which faces the circulating beam, is grounded.

Reaching the neighboring straight section, where the bump is installed ², the beam is bent back to the closed orbit by the bump whose field(typically 10kV for 8cm aperture)decays in 3μ s. The injection scheme offers a possibility to increase the beam intensity through multi-turn injection, though, at present, the beam was injected only one turn.

After optimizing the septum and the bump voltage, the beam was circulated in the ring more than 200 turns as shown in Fig.4. The beam position was consistent with simulation as shown in Fig.5. The observed beam lifetime was 90μ s. The observed vacuum level was 5×10^{-7} Torr at the septum. It explains the beam lifetime to be restricted by the charge transfer with hydrogen in the ring.



Figure 4: Circulating beam signal observed by the beam position monitor (13 of Fig. 1)



Figure 5: Injected beam position at the ring faraday cup(7-2 in Fig. 1) in various septum high voltage(bump off)

3 BETATRON TUNE

In the POP machine, the betatron tune can be changed by changing the focusing and defocusing field separately. To check it, revolution frequency, horizontal tune and vertical tune were measured at injection energy with various ratio of the focusing and defocusing field. The fractional part of

²Recalling the expected horizontal tune, \sim 2.2, the phase advance between each straight section is almost $\pi/2$, which is optimum phase advance for the bump.

tune is obtained as the side-bands of revolution frequency by applying FFT to the beam position monitor signal. As shown in Fig.6, the observed horizontal tune was consistent with simulation. The inconsistency in vertical tune seems to come from beam injection with large amplitude.



Figure 6: Betatron tune in various field setting, (a) Horizontal tune, (b)Vertical tune

4 RF AND BEAM ACCELERATION

The required rf parameters are summarized in table.1. The acceleration time from 50keV to 500keV is 1ms. In the case that the synchronous phase is set to be 20 degree, the rf voltage should be at least 1.3kV during acceleration. We have developed a rf cavity using two rectangular FINEMET ³ cores of $1.1m(width) \times 0.7m(height)$. The thickness of the core is 30mm. A 55kW rf amplifier which consists of two tetrodes(Eimac 4CW25,000) was used. In the first trial of beam acceleration, since the rf voltage was fixed to 1.66kV during the acceleration from 50keV to 374keV, the rf frequency was changed from 624kHz to 1.25MHz as shown in Fig.7.

Fig. 8 shows typical circulating signals observed by inner and outer electrodes of the beam position monitor. It indicates the shift of beam position from the inner side to the outer side during acceleration. The observed revolution frequency and synchrotron frequency were changed from 610kHz to 1.251MHz, and from 24.06kHz to 16.78kHz with accuracy of 6.1kHz, respectively. The synchrotron frequencies agree well with the values calculated from small amplitude approximation.

5 CONCLUSION

A 500 keV POP FFAG synchrotron was constructed at KEK, and its commissioning up to rf acceleration was successfully carried out. All the results show good agreement with calculation. For example, the observed fractional part



Figure 7: Change of rf frequency during acceleration from 50keV to 374keV



Figure 8: The circulating beam signals observed by the beam position monitor. (upper) inner horizontal electrode, (lower)outer horizontal electrode, The ranges are 500 mV/div, $200 \mu \text{sec/div}$.

of horizontal betatron tune was around 0.2. The beam transport and injection tuning showed that the observed beam orbit is consistent with calculation. The acceleration from 50keV to 374keV within 0.6ms was demonstrated.

6 ACKNOWLEDGMENT

We wish to thank to K. Ikegami, C. Kubota, and M. Yoshii, for their grateful efforts while constructing POP machine. We would like to thank K. Niki, M. Muto, T. Adachi and K. Noda for their significant contributions to this work.

7 REFERENCES

- [1] Y. Mori et al., Proceedings of EPAC, 1998, p.299-301
- [2] C. Ohkawa, Proc. of annual meeting of JPS(1953)
- [3] K. R. Symon et al., Phys. ReV. 103(1956)1837
- [4] A. A. Kolomensky et al., ZhETF 33(1957)298
- [5] D. W. Kerst et al., Revew of Scientific Instrument 28(1957)970
- [6] Y. Mori et al., Proceedings of 12th Symposium on Accelerator Science and Technology, Wako, Japan 1999

³For the detail of FINEMET, see [1]