「加速器」Vol. 10, No. 2, 2013（125－127）

## 新博士紹介


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Degree　Doctor (Engineering)
Date　2013. 3. 25
Title　Study of serpentine acceleration in zero-chromatic FFAG accelerators

### 1. Introduction

High beam power accelerators to produce intense secondary particle beams are desired for many applications such as Accelerator Driven System (ADS)[1]. One of a possible candidate is a Fixed-field alternating gradient (FFAG) accelerator[2]. There are two types of FFAG; non-scaling type and scaling type. Scaling FFAG ring is composed of non-linear magnetic fields so that the betatron tune is constant for every particle momentum. On the other hand, in non-scaling FFAGs, use of linear magnetic field leads to a change of betatron tune with acceleration.

In order to obtain large current beam in scaling FFAG accelerators, the acceleration scheme with fixed rf frequency called stationary bucket acceleration[3] has been considered. On the other hand in non-scaling FFAG, new type of fixed rf frequency acceleration scheme called serpentine acceleration[4] has been developed. For both types of FFAG accelerators, only relativistic energy particles are suitable for a fixed rf frequency acceleration. However, if a serpentine acceleration scheme is applied to scaling FFAG, high-power beam with c.w. mode can be achieved even in the non-relativistic energy region. The purpose of this study is to examine a serpentine acceleration scheme in scaling FFAG both theoretically and experimentally, allowing fixed rf frequency acceleration in non-relativistic energy region.

### 2. Longitudinal dynamics with fixed rf frequency

#### 2.1 Longitudinal Hamiltonian

In longitudinal particle dynamics with constant rf frequency acceleration in scaling FFAGs, the phase and energy difference per revolution are described analytically. Assuming that the energy gain is uniformly distributed around the ring, we obtain the phase and energy equations of motion.

$$\frac{d\phi}{d\Theta} = h\left[\frac{(E_S^2 - m^2)^{\frac{1-\alpha}{2}}}{E_S} E(E^2 - m^2)^{\frac{\alpha-1}{2}} - 1\right], \tag{1}$$

$$\frac{dE}{d\Theta} = \frac{eV_0}{2\pi}\sin\phi , \tag{2}$$

where $m$ is the rest mass, $V_0$ is the rf peak voltage per turn, $h$ is the harmonic number, $Es$ is the stationary energy defined by the energy of a synchronous particle and $\Theta$ is the azimuthal angle in the ring. We choose the energy variable $E$ canonically conjugate to the coordinate variable $\phi$. Then Eqs. 1 and 2 derive the longitudinal Hamiltonian:

$$H(E, \phi; \Theta) = h\left[\frac{1}{\alpha+1}\frac{(E^2 - m^2)^{\frac{\alpha+1}{2}}}{E_S(E_S^2 - m^2)^{\frac{\alpha-1}{2}}} - E\right] + \frac{eV_0}{2\pi}\cos\phi \tag{3}$$

with momentum compaction factor $\alpha$, Detail derivation process is written in Ref. [5].

#### 2.2 Longitudinal phase space in non-relativistic energy region

When the rf frequency is fixed near the transition energy, serpentine channel appears between two stationary buckets. With appropriate selection of the transition energy and rf frequency, serpentine acceleration can be achieved in non-relativistic energy region as shown in **Fig.1**.

#### 2.3 Minimum rf voltage to open a serpentine channel

The lower limit of rf voltage $V_{min}$ to connect fixed


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points, called minimum rf voltage, is derived from Eq. (1) as

$$V_{min} = \frac{\pi h}{e}\left[\frac{1}{\alpha+1}\left(\frac{P_{s1}^2}{E_{s1}} - \frac{P_{s2}^2}{E_{s2}}\right) + (E_{s2} - E_{s1})\right] \quad (4)$$

with momenta $P_{s1}$ and $P_{s2}$ corresponding to stationary energies $E_{s1}$ and $E_{s2}$, defined in **Fig. 1**.

### 2.4 Phase acceptance of serpentine channel

Phase acceptance $\Delta\phi_{acc}$ defined in **Fig. 1** is an important parameter to determine the injected beam length in the longitudinal direction. Phase acceptance at the stationary energy below transition is written by

$$\begin{aligned}\Delta\phi_{acc} &= \pi - \phi \\ &= \pi - \arccos\left[\frac{V_0 - 2V_{min}}{V_0}\right], \end{aligned} \quad (5)$$

with the minimum rf voltage. Once ring parameters, i.e. minimum rf voltage is obtained, phase acceptance is determined by the rf voltage as shown in **Fig. 2**.

## 3. Experiment

The demonstration of serpentine acceleration was carried out in electron scaling FFAG accelerator, designed as an F-D-F triplet radial sector type of scaling FFAG.

### 3.1 Demonstration of serpentine acceleration

The experiment is carried out by changing the initial rf phase at the injector. The phase is shifted with respect to the rf phase of the cavity. Beam current in the ring is measured by the movable Faraday cup for every initial phase. During measurements, the position of the movable Faraday cup is fixed at extracted beam energy orbit. Only particles accelerated in the serpentine channel can be measured at the Faraday cup in this experimental set up. Results are shown in **Fig. 3**.

With the measurement of the phase range where particles were accelerated with serpentine channel, we demonstrated serpentine acceleration in scaling FFAG.

### 3.2 Phase acceptance measurements with rf voltage

As shown before, the theoretical phase acceptance of serpentine channel becomes bigger with rf voltage. To verify this feature, we measure phase acceptances

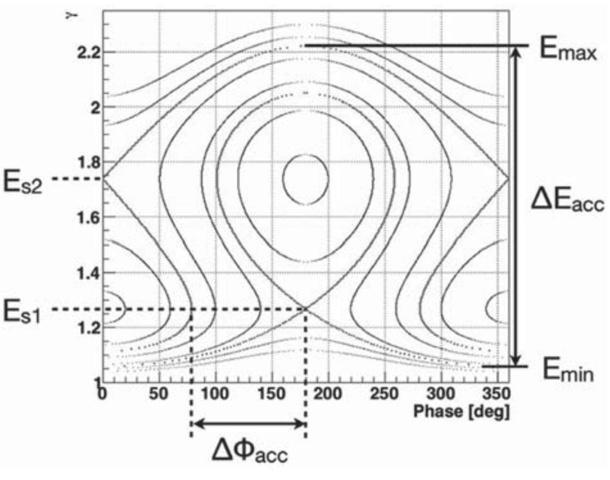


**Fig. 1** Longitudinal phase space with definition of the phase acceptance $\Delta\phi_{acc}$.

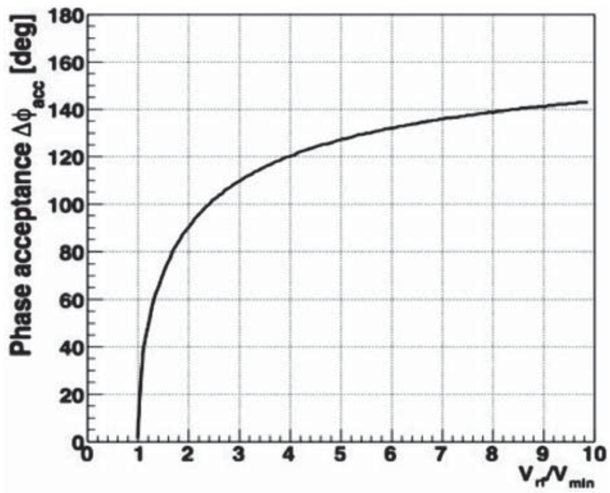


**Fig. 2** Phase acceptance $\Delta\phi_{acc}$ of serpentine channel with rf voltage.

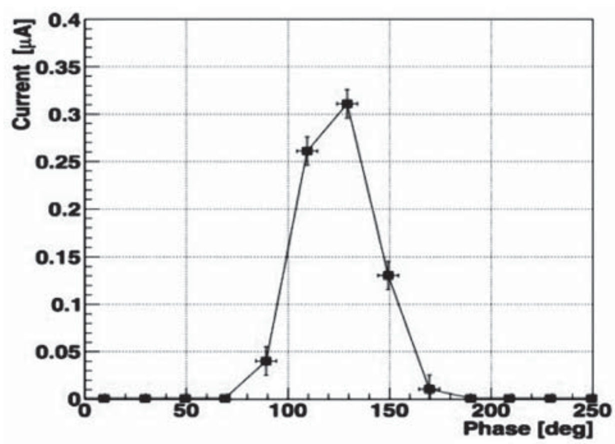


**Fig. 3** Beam current at the Faraday cup.

with five different rf voltage.

Measured and analytical phase acceptance are presented in **Fig. 4**. From this result, the measurement results are consistent with the analytical results. Details about experimental apparatus and methods of analysis are written in Ref.［5］.

## 4. Summary

We have confirmed that serpentine acceleration in scaling FFAG can be applicable not only in relativistic energy region but also in non relativistic energy region theoretically. The world's first experiment on serpentine acceleration in scaling FFAG has been conducted with electron scaling FFAG machine to demonstrate this new fixed rf frequency acceleration scheme.

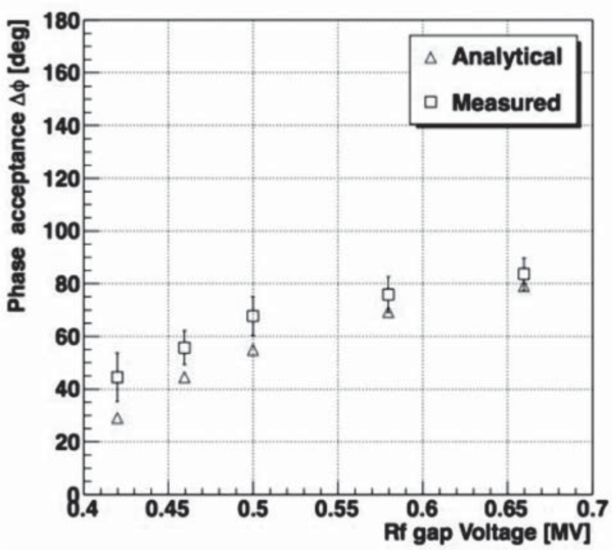


**Fig. 4** Phase acceptances with rf voltage.

## 5. Future work

I have been working for JAEA as a postdoctoral researcher since April, 2013. My topic of research is about the effect of injected beam conditions and materials of charge exchange foil on the residual dose around the foil. I would like to contribute to this work with my previous experiences.

## References


1） K. Mishima, et.al., Journal of Nuclear Science and Technology, vol.44, No3 Special Issue on GLOBAL 2005, p.499-503, 2007.

2） E.D. Courant and H.S. Snyder, Theory of the Alternating-Gradient Synchrotron, Annuals of Physics, p.1-48, 1958.

3） T. Planche, et.al., Scaling FFAG rings for rapid acceleration of muon beams, Nucl. Instr. and Meth. A, Vol.523, Issues 1-2, p.25-49, 01, May 2004.

4） S. Machida, et.al., Nature Physics, Vol.8, No.3, p. 243-247, 2012.

5） E. Yamakawa, Study of serpentine acceleration in zero-chromatic FFAG accelerators, PhD thesis, Graduate School of Engineering, Kyoto University, 2013.