EXPERIMENTAL STUDY TOWARDS HIGH BEAM POWER FFAG [*]

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Abstract

The FFAG complex at KURRI is not only the first proton FFAG accelerator facility for beam users but the one aiming to have high beam power. The talk will present various efforts to increase beam power for the last few years and systematic strategy in near future toward the space charge limit.

FFAGS IN KURRI

Kumatori Accelerator driven Reactor Test (KART) project has been started at Kyoto University Research Reactor Institute (KURRI) since the fiscal year of 2002, aiming to demonstrate the basic feasibility of accelerator driven sub-critical system (ADS) and to develop a 150 MeV proton FFAG accelerator complex as a neutron production driver [1]. The accelerator complex was originally composed of a spiral-sector induction-accelerator, and two radial sector FFAG accelerator [2]. As a first stage, the FFAG accelerator complex has been achieved to output 100 MeV-0.1 nA proton beams at 30 Hz repetition and ADS experiments have been started in March 2009 [3].

In order to raise beam power of the FFAG, the injectors of the FFAG main ring was replaced by an 11 MeV linac with H^- ion source [4] in fiscal year of 2010. With the charge stripping injection of H^- beam, the output beam current of the main ring has reached 1 nA in March 2011 and 10 nA in 2012 with 20 Hz operation. Also acceleration up to 150 MeV has been achieved in 2012. The increased beam intensity attracted beam users in material sciences. Irradiation experiments for material radiation effects are undergoing.

Though the performance of the FFAG is improved every year, it is still far from the limiting current determined by the injector linac. The maximum output of the linac is estimated 3×10^{12} particles per pulse, which corresponds to 10 μA in 20 Hz operation. Main beam loss occurs at beam injection and capture in the main ring. Optimizations of the charge stripping injection and capture efficiency are in progress.

INTENSITY UPGRADE IN KURRI

H^- Injection without Bump System

H^- beams are injected into the FFAG main ring through a charge stripping foil made of carbon. This injection scheme makes it possible to inject a beam at the center of phase space already occupied by a previously injected beam. The circulating beam should escape from the stripping foil as fast as possible, otherwise undesirable effects happen, such as multiple scattering, energy losses and overheating of stripping foil. One method to escape from the stripping foil after injection is to make a bump-orbit. This works very efficiently, but it needs a complicated system. In our facility a fast acceleration is adopted to escape from the stripping foil, using the characteristic feature of FFAG accelerator (Fig. 1). The dispersion is $dR/dE = 2.4$ cm/MeV at the injection energy and rf amplitude is $V = 4$ kV. Therefore, the number of foil-hits for a bunch will be more than 100. This number may be reduced by using offset injection in horizontal space.

Table 1: Machine and Beam Parameters

Parameter	Value
Linac	
Repetition	<200 Hz
Peak current	<5 mA
Pulse length	<100 μs (uniform)
Energy	11 MeV±30 keV (at σ)
Main ring	
Energy	11∼100 or 150 MeV
Field index, k	7.5
Revolution frequency	1557 kHz at injection
Rf voltage	<4 kV

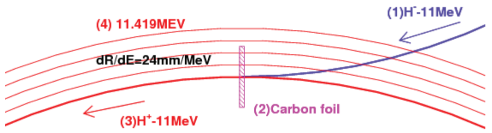

Figure 1: Scheme of charge-strip injection using dispersion.

The stripping foil is installed inside the main magnets and its radial position can be remote controlled. The foil is made of carbon whose dimensions are 25 mm×25mm. The thickness is assumed to be 20 μg/cm^2. Stripping efficiency is higher than 99 %.

Averaged particle energy loss, which is calculated by Bethe's formula, is ΔE_{loss}=760 eV for a 20 μg/cm^2. This energy loss raises the synchronous rf phase as

$$V \sin \phi_s = V \sin \phi_a - \Delta E_{loss} ,$$

where ϕ_a is the accelerating phase related to the

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synchronous-energy gain directly. Longitudinal emittance growth occurs when the beam energy reaches the boundary of the striping foil, because only low energy part of the beam loses energy. In addition, the synchronous phase jumps at the boundary. Those effects reduces the capture efficiency (see Fig. 2).

Maximum temperature rise of the foil was calculated with the energy loss taking into account the radiation cooling. For example, the maximum temperature rise was estimated to be 300 K, when a 5 mA (peak) beam of 100μs length are injected and all the particles hit the stripping foil over 100 turns. Though the limiting temperature rise of the foil is not clear this moment, the temperature rise can be the dominant limitations of the beam intensity in the future.

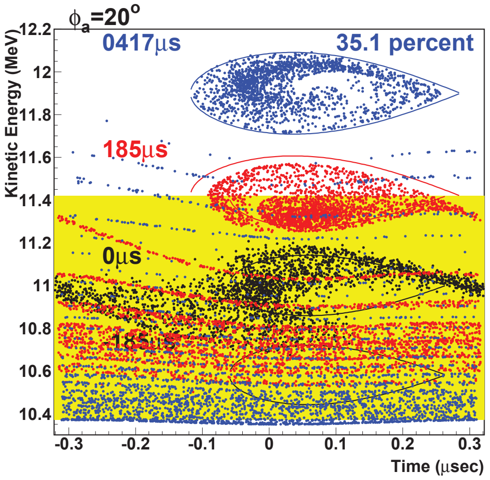

Figure 2: Beam loss caused by the energy loss at charge stripping foil (simulation). Yellow-hatched region corresponds to the energy region whose closed orbit intersects the foil.

Optimization of Charge Stripping Injection

There is a trade-off in choosing the synchronous phase at injection energy. From the view point of suppressing energy loss and transverse emittance growth, initial acceleration speed should be fast. On the other hand, rf buckets stays long time at the injection energy in order to capture much particles delivered from the linac.

Systematic experimental study has been started to optimize the rf capture optimization, capture efficiency measurements with different ϕ_s.

Additional Cavity

An additional rf cavity has been developed, and is ready to be installed in the FFAG main ring. Magnetic alloy (MA) cores are loaded in the new cavity, and the cores are cooled by circulating silicon oil directly.

Increasing rf voltage with this cavity enables to accelerate rapidly at higher ϕ_s and/or enlarge the bucket area to increase the number of particle per pulse. In addition, rapid acceleration reduces the number of foil scattering at the injection energy.

Figure 3: Additional rf cavity to be installed (one half).

Beam Stacking at High Energy Orbit

Some users desire low spill rate (~10 Hz) for the experiments e.g. neutron radiography using TOF which needs to get rid of contamination from the pulse of different timing. FFAG rings can provide long interval pulse for users, while the machine operation itself is kept at high repetition rate by using rf stacking after acceleration [5].

Optimistically, the peak current of the output beam becomes multiplication of number of stack. However this is not realistic because of the growth of the momentum spread due to Liouvilles theorem [6]. Simulation studies showed that adiabatic landing, where the rf voltage is adiabatically reduced, is effective to suppress the momentum spread of the stacked beam. Experimental study is necessary.

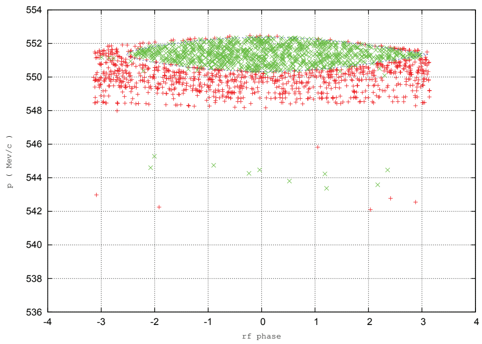

Figure 4: Simulation of stacking at high energy orbit.

EXPERIMENTS FOR FUTURE HIGH CURRENT FFAG

By means of the efforts described above, the intensity of our FFAG will approach space-charge limit. FFAG has larger potential to accelerate high current beams because of the constant guide field.

Space Charge Limit

The space charge limiting current is usually determined by the betatron tune shift by the internal field, which is measured by the Laslett tune shift,

$$\Delta\nu = \frac{Nr_0}{\pi\beta^2\gamma^3}\frac{F/B}{\beta_y\epsilon_y(1+\sqrt{\epsilon_x/\epsilon_y})} . \quad (1)$$

Though there are unknown parameters such as form factor F and bunching factor B, it is roughly evaluated 0.3 for 0.6×10^{12} protons (4μA in 20 Hz operation). This value is below the number of particles out of the injector linac. It is not clear that the Laslett tune shift is a good measure to evaluate the intensity limit even for a strongly non-linear synchrotron like FFAG.

Multi-fish

Repetition rate can be multiplied with keeping the peak intensity by multi-fish operation [7]. In this scheme, two or more rf acceleration signals are mixed at a certain time difference, such that the accelerating buckets at different synchronous energies run simultaneously. The main issue of this acceleration scheme is the interference of different rf signals, which works as a perturbation on the motion inside a bucket. The interference is obviously stronger if the frequencies of the two rf signals are closer.

Acceleration with two buckets can be easily tested in our FFAG with the help of the second rf cavity. The two rf cavity works with a certain time difference. It is not necessary to fill both of two buckets by particles, in order to see the bunch deformation due to the other bucket.

The injector linac can operate up to 200 Hz, which corresponds to the 4 times of the accelerating time in the FFAG main ring.

Continuous Acceleration

Continuous acceleration like a cyclotron is also possible in FFAG, if it can operate at a constant rf frequency.

- inside-bucket acceleration
- serpentine acceleration
- harmonic number jump
- vertical FFAG at ultra-relativistic energy region

Inside-bucket acceleration is available when the bucket hight is larger than the energy range of the acceleration. The rf frequency is constant and the beam can be continuously accelerated by the rf. Serpentine acceleration [8] is the improvement of this. The bucket height is enlarged by choosing transition energy between injection and extraction. The serpentine acceleration is characterized by serpentine path in longitudinal space. In the harmonic number jump acceleration [9], the rf frequency and slippage factor are carefully chosen such that synchronous particle always see an accelerating phase but different harmonic number. Vertical FFAG [10] can be operated continuously in ultra-relativistic energy region.

In these FFAGs under continuous operation, interactions between neighboring orbits can take an important role for the intensity limit. What we should take into account are (1)space-charge induced COD, (2) consequent deviation of external focusing, and (3) tune shift by orbit interaction.

Dipole Mode Tune in a Continuous FFAG

Let us discuss the effect of interaction between neighboring orbits in a continuous FFAG. We introduce a simple model;

- Perfect scaling with designed tune ν_0
- Electric field is confined by a horizontally wide rectangular chamber
- Turn separation Δx is larger than the beam size, but still much smaller than the vertical aperture height h.

This situation is true in a very rapid accelerating (~several 10 turns to the top energy) continuous FFAG. Let $r_s(\phi)$ be a static spiral orbit in the mid-plane, where ϕ is not restricted in [0,2π] but increases with turn number. This is not unique because no boundary condition like 'closed' is required. The static orbit affects the space charge. Zotter [11] showed that the electric potential induced by a line charge λ at (x_0, y_0) is given by

$$-\frac{\lambda}{4\pi\epsilon_0}\ln\frac{\cosh(\frac{\pi}{2h}(x-x_0))-\cos(\frac{\pi}{2h}(y-y_0))}{\cosh(\frac{\pi}{2h}(x-x_0))+\cos(\frac{\pi}{2h}(y-y_0))} . \quad (2)$$

for parallel plate boundary with half height h. Differentiating this with respect to x, it turned out that the horizontal field is rapidly decreasing with $x-x_0$ (Fig. 6). Therefore, we assume the tune shift due to the static-orbit shift is negligibly small.

Define a horizontal coordinate $x(\phi)$ for each azimuth, originated at $r_s(\phi)$. Equation of motion for $x(\phi)$ is

$$\begin{aligned}\frac{d^2x(\phi)}{d\phi^2} = -\nu_0^2x(\phi) &+ \sum_{n=1}^{\infty}\alpha_n\left[x(\phi+2n\pi)-x(\phi)\right] \\ &+ \alpha_n\left[x(\phi-2n\pi)-x(\phi)\right] \quad (3)\end{aligned}$$

where α_n is the linear coefficient of space charge force, which is rapidly decreasing positive function of n. Here the lowest and the highest energy orbit are out of consideration. Let us assume the general solution of Eq. (3) in form $x(\phi) = X\exp(i\nu\phi)$ where X is a constant. The Eq. requires

$$\nu^2 = \nu_0^2 + \sum_{n=1}^{\infty}\alpha_n\sin^2 n\pi\nu \quad (4)$$

and thus the coherent dipole tune ν is higher than the original tune ν_0.

Positive tune shift by space-charge is easy to understand. A part of orbit with a small displacement always feels stronger repulsing force from the next, and this force works as a focusing about $x(\phi) = 0$.

Similar discussion is possible for vertical oscillation. It results in the coherent tune reduction as usual case.

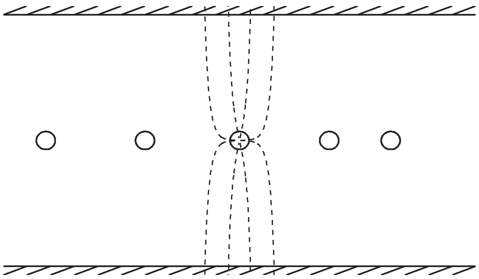

Figure 5: Cross-section of the chamber under consideration. Beam in each energy orbit (circles) produces electric field (dotted lines).

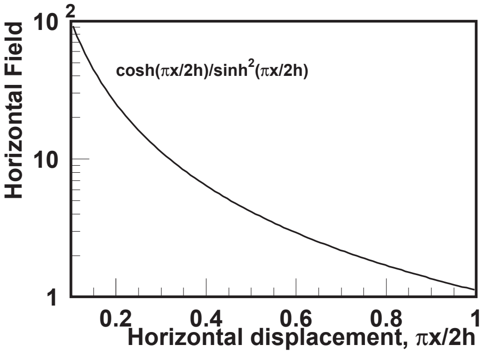

Figure 6: Space charge field of two parallel line charges. Parallel plate boundary of half-width h is considered.

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REFERENCES

[1] K. Kawase and M. Inoue, Proc. of APAC 98, Tsukuba, Japan, p. 104-106 (1998).

[2] T. Uesugi *et. al.*, Proc. of EPAC 08, Genova, Italy, p. 1013-1015 (2008).

[3] C. H. Pyeon *et al.*, J. Nucl. Sci. Tech. Vol. 4, No. 12, p. 1091-1094 (2009).

[4] K. Okabe *et. al.*, Proc. of IPAC 10, Kyoto, Japan, p. 3897-3899 (2010).

[5] S. Machida, FFAG Workshop 2003, BNL, October 13-17, (2003).

[6] Y. Ishi *et. al.*, Proc. HB2012, Beijing, China, p. 64-67 (2012).

[7] Y. Mori *et. al.*, Proc. of PAC2001, Chicago, Illinois, USA, p. 588-590 (2001).

[8] E. Yamakawa *et. al.*, Nucl. Inst. and Meth. A , Vol. 716, p. 46-53 (2013).

[9] T. Planche *et. al.*, Proc. of PAC 09, Vancouver, Canada, p. 4308-4310 (2009).

[10] S. J. Brooks, Proc. of IPAC 12, New Orleans, Louisiana, USA, p. 406-408 (2012).

[11] B. Zotter, Nucl. Inst. and Meth. Vol. 129, p. 377-395 (1975)