RF CAPTURE OF BEAM WITH CHARGE-EXCHANGING MULTI-TURN INJECTION

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Abstract

In the fixed field alternating gradient (FFAG) synchrotron in Kyoto university research reactor Institute (KURRI), charge exchange injection was adopted since 2011. The charge stripping foil is located on the closed orbit of the injection energy, and no bump orbit system is used. Instead, the injected beams escape from the stripping foil according to the closed-orbit shift due to acceleration. In this scheme, it is important to minimize the number of foil hitting, which causes emittance growth and foil heating. In this paper, the rf capture is studied by means of simulation.

INTRODUCTION

Kumatori accelerator driven reactor test 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 an 150 MeV proton FFAG accelerator complex as a neutron production driver [1]. The accelerator complex was composed of a spiral-sector induction-acceleration FFAG accelerator, and two radial sector FFAG accelerator [2]. As a first stage, the FFAG accelerator complex has 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 for the FFAG main ring was replaced by an 11 MeV linac with H^- ion source [4] in fiscal year of 2010. Here, 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.

However, the circulating beam should escape from the stripping foil as fast as possible, otherwise undesirable effects happens, such as multiple scattering, energy losses and overheating of stripping foil (3rd section). 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. The dispersion is dR/dE=24 mm/MeV at the injection energy and rf amplitude is V=4 kV. Therefore, the number of foil-hits will be more than 100.

With the charge-exchange injection, the output beam current of the main ring has reached 1 nA in March 2011 in this scheme. Now the transport efficiency between the linac and the main ring is still increasing by re-alignment of the magnets and careful optimizing of the optics. In addition, the improvement of the rf, especially in the capture stage, is necessary.

In the next section, the present rf operation are briefly shown. The third section describes the things which should be taken into account. The simulation studies of rf capture and their results are shown in the fourth section.

Table 1: Machine and Beam Parameters

Parameter	Value
Linac	
Peak current	$<$5 mA
Pulse length	$<$100 μs (uniform)
Energy	11 MeV$\pm$30 keV (at σ)
Main ring	
Field index, k	7.5
Revolution frequency	1557 kHz at injection
Rf voltage	$<$4 kV
Foil width	25 mm
Energy loss	760 eV or 380 eV

PRESENT OPERATION

In this moment, the beam was captured by a accelerating bucket with the constant ϕ_a of 30 deg, and no special treatment is done at the injection stage.

With this rf, output current of 1 nA has been achieved. A beam study with chopping injected beam pulses to 5μs, a slow beam loss was observed in first several hundred micro-seconds as shown in Fig. 1. The beam loss is probably caused by the bucket mismatch.

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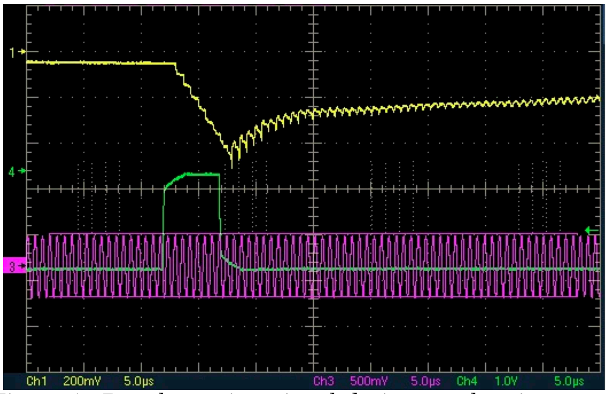

Figure 1: Bunch monitor signal during acceleration up to 100 MeV (CH1, yellow). CH3 (pink) shows rf source signal and CH4 (green) gate signal of beam chopper at ion source: 5 μs/div.

EFFECTS OF STRIPPING FOIL

The stripping foil is installed inside the main magnets and its radial position can be remote controlled. The foil is made of a carbon whose dimensions are 25 mm$\times$25mm. The thickness is assumed to be 10 or 20 μg/cm^2. Stripping efficiency is higher than 98% for this thickness.

Averaged particle energy loss, which is calculated by Bethe's formula, is ΔE_{loss}=760 eV for a 20 μg/cm^2 foil and 380 eV for 10 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 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.

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 840 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.

SIMULATION

Longitudinal multi-particle simulation studies were done in order to optimize the capture rf operation. Effect of the stripping foil was simulated by a constant energy loss each turn for all particles whose energy is less than a threshold of 11.42 MeV: At this energy the closed orbit reaches the outer edge of the stripping foil, which is assumed 10 mm from the center. That means, all particles are assumed to circulate on the closed orbit corresponding to their energy and horizontal oscillations were neglected.

Macro-particles were successively injected in the first 100 μs. The energy distribution of the particles was Gaussian centered at 11 MeV and 30 keV width at standard deviation.

The rf was applied with a constant amplitude of 4 kV. As Fig. 2 shows, accelerations were done with different acceleration phases (ϕ_a) from lower frequency than the injected beam, such that the synchronous energy reaches 11 MeV at the center of beam pulse in order to optimize the capture efficiency.

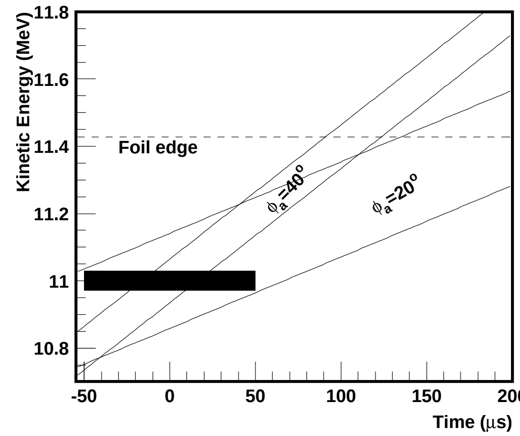

Figure 2: Acceleration scheme in simulation study. Bucket area regions are plotted by surrounding lines, and black square shows injected beam.

Capture Efficiency

Capture efficiency was defined by the number fraction of particles which exceed a threshold energy of 13 MeV after sufficient acceleration time.

Figure 3 shows the simulation results. Dashed line shows the result without the energy losses at foil. The decreasing function corresponds to the fact that the bucket area is decreasing with increasing ϕ_s.

With the finite energy losses, the capture efficiency was reduced as Fig. 3. The reduction at high ϕ_a corresponds to the reduction of the synchronous phase due to the energy loss. On the other hand, the reduction at low ϕ_a is caused by the emittance growth at the boundary of the stripping foil.

Number of Foil Hits

The integrated number of foil-hits by macro-particles, N_{hit}, are counted in the same simulations. Figure 4 shows this. In the Fig. circle markers plot N_{hit} for all particles

The N_{hit} is around 1500 at $20^o < \phi_a < 40^o$ for 20μg/cm^2 foil. This is too much. However, the most part of the foil hits are done by the particles which dropped out of the rf-bucket. Those particles continuously hit the foil until the closed orbit of the particles reaches inner edge of the stripping foil, and thus increases the N_{hit}. The average number of foil-hits are calculated again only with the accelerated particles (Fig. 4, with triangles). It is shown that the N_{hit} significantly increases with decreasing ϕ_a, because the rf-bucket stays long time around the foil-boundary.

In order to reduce the foil overheating, it is effective to use a high-frequency beam-chopper, which can produce a micro structure of the linac output beams synchronizing with rf wave.

Simulation was done with restricting the injected beam inside the rf phase of 0$\sim$130^o. Accelerating phase of $\phi_a = 20^o$ was chosen here. Figs. 5 and 6 show the simulated beam distribution at 50 and 250 μs, respectively.

The number of foil-hitting was reduced to 460/(injected-particle). The fraction of accelerated particles was 26.4% of the linac beam before chopping.

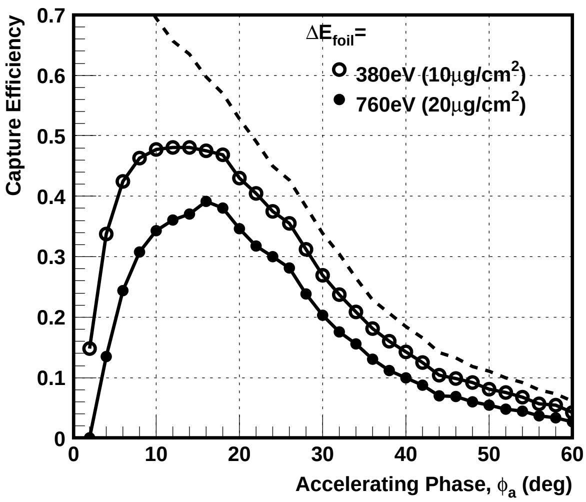

Figure 3: Capture efficiencies as functions of accelerating rf phase for different energy losses at stripping foil. Dashed line shows the result without energy loss.

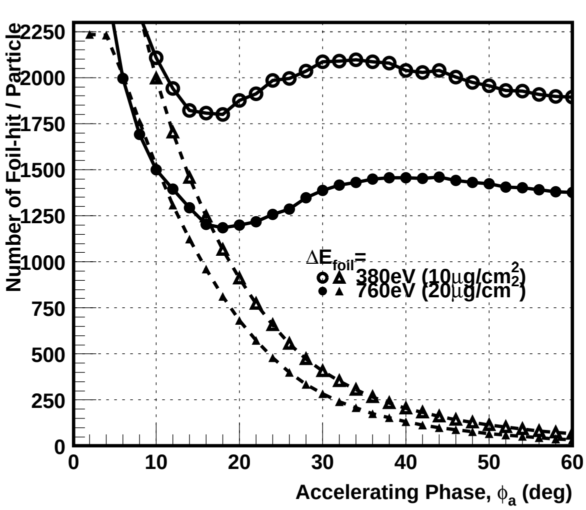

Figure 4: Averaged Number of foil hit per particle (N_{hit}). Circles are for all particles, while lost particles are neglected in triangle markers.

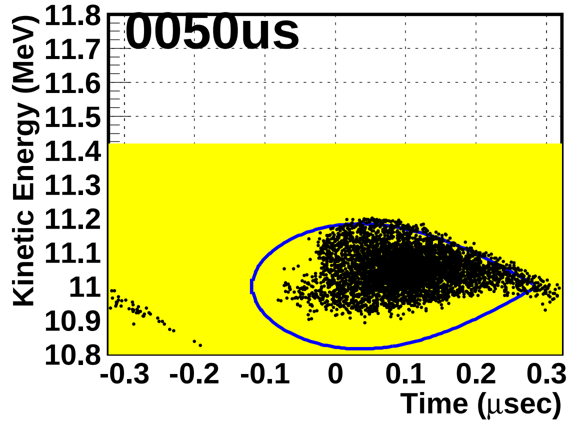

Figure 5: Phase distribution at t=50 μs. Yellow hatched region shows the energy at which closed orbit hits the stripping foil.

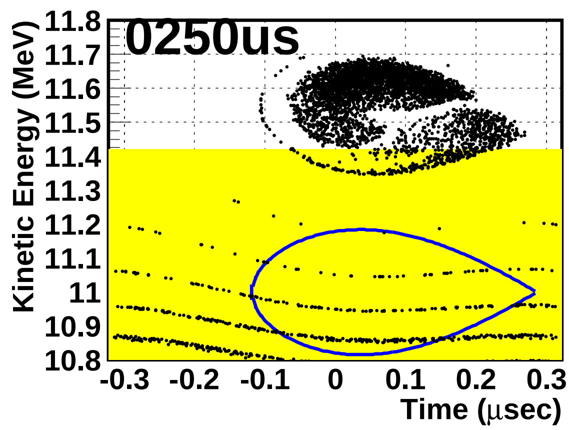

Figure 6: Phase distribution at t=250 μs.

SUMMARY

Simulation studies were done taking into account the energy loss of circulating particles which hits the stripping foil. The capture efficiency takes maximum around the accelerating phase of 20^o. Overheating of the stripping foil can be the problem, but this is overcome if we have a high frequency chopper at the injector beam line.

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