ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPAL030

IMPROVEMENT OF RF CAPTURE WITH MUTI-TURN H$^-$ INJECTION IN KURRI FFAG SYNCHROTYRON

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Abstract

In the KURRI FFAG synchrotron, charge-exchanging multi-turn injection is adopted with a stripping foil located on the closed orbit of injection energy. No injection bump orbit system is used and the beam escapes from the foil according to the closed-orbit shift by acceleration. The particles hit the foil many times and the emittance grows up during the injection. In this paper, the capture efficiencies are studied with different rf process, including adiabatic capture .

INTRODUCTION

Accelerator complex of fixed field alternating gradient (FFAG) synchrotrons has been developed in Kyoto university reasearch reactor institute (KURRI), aiming to demonstrate the basic feasibility study of accelerator driven sub-critical system (ADS). Originally the accelerator complex was composed of three cascade FFAG rings [1] connected to subcritcial reactor in Kyoto university critical assembly (KUCA). The ADS studies with this system were started in March 2009 [2].

In 2011, the injector was replaced by linac and H$^-$ ion beams of 50 μs long were injected directly to the final FFAG ring with charge exchange multi-turn injection [3, 4]. With this upgrade the accelerated beam intensity has been increased up to 1 nA in 20 Hz repetition, but this number is only 0.25 % of the H$^-$ beam from the linac.

In ordinary operation, the injected beam is captured with a moving bucket. The charge stripping foil is located on the closed orbit of the injection energy and no bump orbit system is employed. The injected particles hit the foil for about 300 times until accelerated beyond the energy at which the closed orbit crosses the foil. That is why the acceleration has to be fast enough, otherwise the emittance grows up and a part of the beam is lost during the injection. In fact, a rapid beam loss was observed right after the injection. Survival ratio at 1 ms after the injection is estimated to be ~3 %. Though betatron resonance is also possible, the effects caused by the foil is a big reason of the beam loss.

Simulation studies have been done with taking into account the energy loss [5] and transverse scattering at the foil, based on GEANT4 [6] code. There it was found that the longitudinal eimittance drastically grows up aroud the outer boundary of the foil, because of the synchrnous phase jumping (Fig. 1) [5]. In presence of energy loss ΔE per turn, the synchronous phase is shifted as

$$V \sin \phi_s = V \sin \phi_{s0} + \Delta E,$$

where ϕ_s and ϕ_{s0} are the synchronous phases with and without ΔE. In addition, emittance grows in transverse spaces at 7 π mm-mrad/0.1 ms and finarly a part of the beam is lost [7]. The simulated capture efficiencies were 35% without transverse scattering and 26% with it. The efficiency was still higher than the experimemtal results.

In this paper, simulation studies of a capture with stationary buckets are tested in order to improve the capture efficiency.

Table 1: Parameters of FFAG Main Ring and Injector

Parameter	Value
Particle	Proton
Kinetic energy	11 – 150 MeV
Revolution frequency	1.558 – 3.85 MHz
Twiss (β_x, β_y)	(2.9 m,2.5 m) at foil
Dispersion	24 mm/MeV
Acceleration speed	1.4 keV/turn

ACCELERATOR AND FOIL

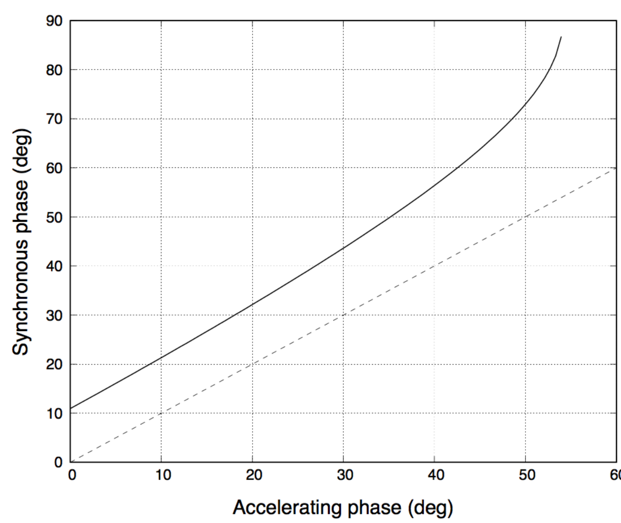

Figure 1: Synchronous phase shift in presence of energy loss at foil (Solid). The energy loss is assumed constant (760 keV).

KURRI FFAG Synchrotron

The KURRI FFAG synchrotron accelerates proton beams of 11 MeV up to 100 MeV or 150 MeV. This machine is so called *radial sector scaling FFAG*, at which the field strength is designed such that $B(r)$ along a radius is proportional to

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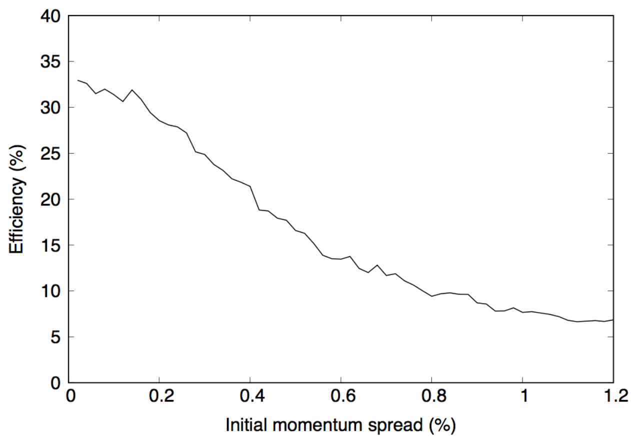

Figure 2: Capture efficiency depending on initial momentum spread.

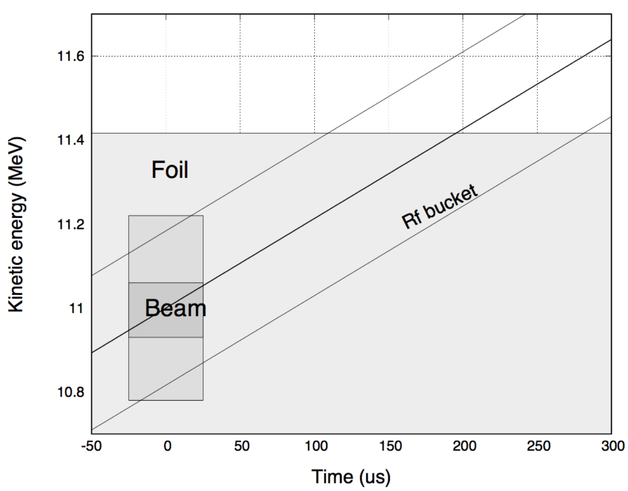

Figure 3: Longitudinal space swept by rf bucket. Snmall hatched region shows injected beam.

r^k. Dispersion function is therefore $(k+1)r$, where r is the closed orbit radius. In reality, because of the scaling field imperfection, the field index k is gradually varying from 7.0 at the injection to 7.7 at extraction energy orbit, while the designed value was 7.6. Orbit shift due to the acceleration is 24 mm/MeV at the injection energy. Betatron tunes at the injection energy were measured to be (3.63, 1.39) [8].

Transverse emittance is assumed to be 5 πmm-mrad in both horizontal and vertical phase spaces, which corresponds to 20 mm in real space. Measured dispersion of the beam line at the injection point was −0.54 m, while the dispersion function of the ring is +0.59 m. Injected beams are captured and accelerated by a moving rf bucket. In ordinary operation, the rf amplitude is fixed at 4 kV and the accelerating phase is 20 deg over the acceleration. Thus the energy gain is 1.4 keV/turn and the orbit shift by the acceleration corresponds to 1 mm/30 turns, or, 50 mm/ms.

The stripping foil is made of carbon whose thickness is 10 μg/cm^2, and its dimension is 25(H)×30(V) mm^2. It is fixed at a three sided holder at the top of the rod, and which limits the vertical aperture. The energy loss and scattering angle of an 11 MeV proton are simulated by GEANT4. Strip efficiency of H^- ion was > 99 %.

SLOW CAPTURE

As Fig. 4 shows the width of rf bucket with $\phi_a = 20^o$, is not enough compared to the injected beam. In order to increase the capture efficiency, slow capture with low acceleration phase was simulated. Here accelerating phase is lineary increased from 0 degree to final value during the injection period of first 50 μs. Figure 5 shows the capture efficiencies for different final phase. Results showed that the capture efficiencies did not change at acceleration phase higher than 15 deg, while it is decreased below it. This process did not improve the capture efficiency.

Adiabatic capture was also simulated. The beam is captured with relatively low voltage rf, and the voltage is and increased such that the bucket area is linearly increasing. The final acceleration phase is fixed at 20 deg. The result is shown in Fig. 6. The efficiency was not improved with this process.

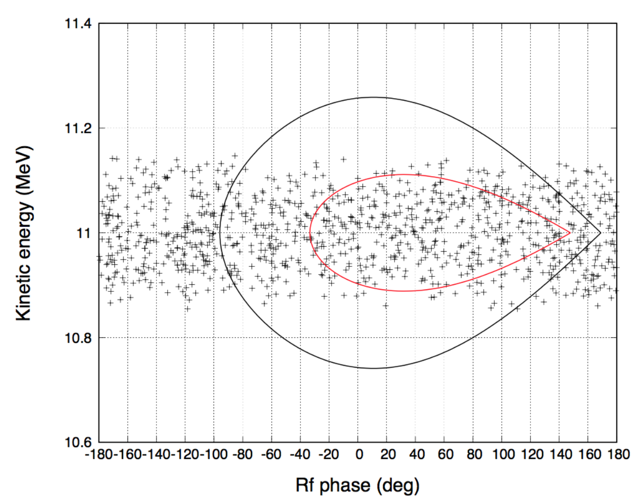

Figure 4: Longitudinal phase space at capture energy. Spots shows the injected beam particles, black and red curves show the rf buckets with accelerating phase of 0^o and 20^o, respectively. In both cases the rf voltage is 4kV.

CONCLUSION

Simulation studies of charge-exchanging multi-turn injection have been done with including the scattering by the foil. The simulated capture efficiency has been reduced to 25.7%, while it was 35% without the scattering.

Slow capture with stationary bucket was tested with fixed rf voltage and lower initial voltage, respectively. Howerver the capture efficiency did not change. The reason is that the capture process of 50 μs is not very long compared to the synchrotron frequency of 7 kHz. To improve the capture efficirency, increasing the rf voltage is essential. Installation of another rf cavity is planned this summer in

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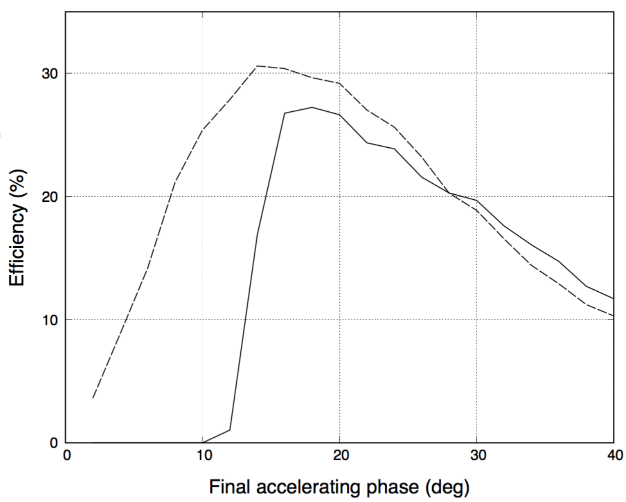

Figure 5: Capture efficiency vs final acceleration phase. Thick curve shows the capture efficiency, and dashed curve shows that with constant phase.

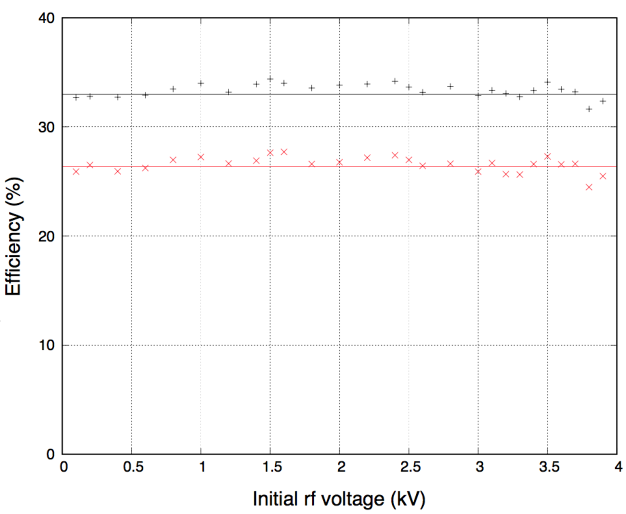

Figure 6: Capture efficiency with adiabatic capture. Red points shows the efficiency, and black ones shows the survival ratio after 1 ms.

order to increase the accelerating voltage. It will reduce the beam loss at the injection.

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