EMITTANCE GROWTH AT CHARGE-EXCHANGING MULTI-TURN INJECTION IN KURRI FFAG

T. Uesugi, Y. Ishi, Y. Kuriyama, Y. Mori
Kyoto University Research Reactor Institute, Osaka, Japan

Abstract

In the KURRI FFAG synhrotron, rapid beam loss of factor 100 is observed right after the injection. In the synchrotron, charge-exchanging multi-turn injection is adopted with a stripping foil located on the closed orbit of the injection energy. No bump orbit system is used and the injected beams escape from the foil acording to the closed-orbit shift by acceleration. The particles hit the foil many times and that is why the emittance grows up during the injection. In this paper, simulation studies are done to estimate the emittance growth and beam losses. The scattering effect at the foil is modelled by GEANT4.

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 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.

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 several turns 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 ~1 %. Though betatron resonance is also possible, the effects caused by the foil is a big reason of the beam loss.

Simulation studies were done with taking into account the energy loss at the foil [5]. There, it was found that the longitudinal emittance grows up, because of the synchrnous phase jumping at the outer boundary of the foil. In presence of the energy loss each turn ΔE, synchronous phase ϕ_s goes up from the nominal value ϕ_{s0} as

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

Table 1: Parameters of FFAG Main Ring and Injector

Parameter	Value
Particle	Proton
Kinetic energy	11 – 150 MeV
Revolution frequency	1.58 – 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

to compensate the energy loss. This happens only when the orbit crosses the foil, so that the rf bucket is discontinuously deformed at the *boundary energy*. Figure 1 schematically shows the effect. A particle around the fixed point of the lower bucket gradually increases its amplitude and finally goes out from the bucket. The discontinuity is less serious with low ϕ_{s0}, but duration time around the boundary energy is longer. Simulation studies resulted that optimum capture efficiency was 30 - 40 % with accelerating phase (ϕ_{s0}) of 10 - 20 degree. This efficiency is much higher than the experimental ratio of the first 1 ms. So this model is not sufficient to explain the beam loss.

In this paper, improved simulation studies are presented. Transverse scattering are included here, and energy loss per turn is more precisely modeled employing GEANT4 [6] code. In addition, effects of mismatch such as Twiss parameter mimatch and dispersion mimatch are studied.

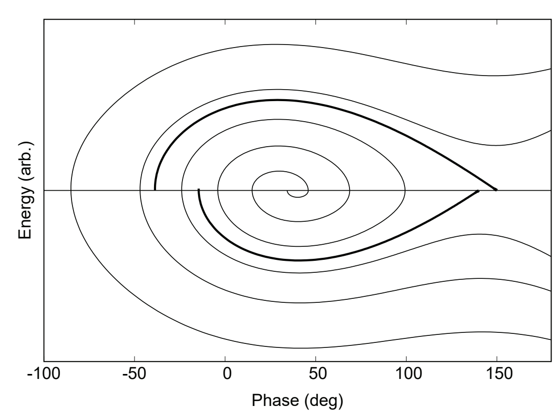

Figure 1: Longitudinal phase trajectories are plotted, where a constant energy loss each turn is assumed only in the lower-half energy region.

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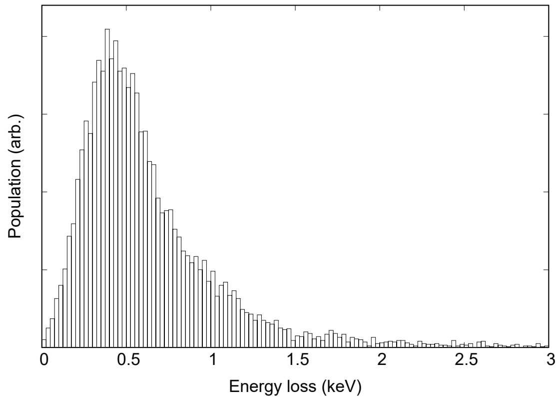

Figure 2: Energy loss at a passage of carbon foil (simulated with GEANT4).

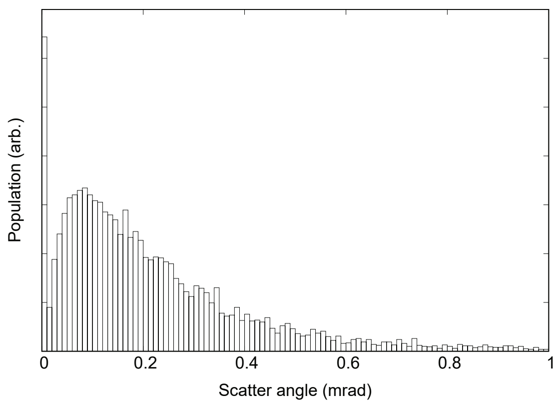

Figure 3: Scattering angle at a passage of carbon foil (simulated with GEANT4).

ACCELERATOR AND FOIL

KURRI FFAG Synchrotron

The KURRI FFAG synchrotron accelerates proton beams of 11 MeV up to 100 MeV or 150 MeV in ordinary operation. 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 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 shifting 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) [7].

Injected beam from the linac has kinetic energy of 11 MeV. Typical emittance is assumed to be 5 πmm-mrad in both transverse 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. 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.

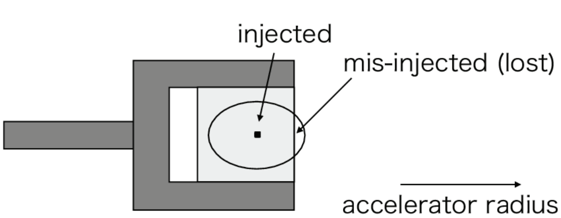

Figure 4: Stripping foil and its holder.

Stripping Foil

The stripping foil is made of carbon whose thickness is 10 μg/cm^2, and its dimensions is 25(H)×30(V) mm^2. It is fixed at a three sided holder at the tip of the rod, and which limits the vertical aperture. The energy loss and scattering angle of an 11 MeV proton are simulated by GEANT4. Figure 2 and 3 shows the distribution of lost energy and scattering angle, respectively. Strip efficiency of H$^-$ ion was > 99 %.

SIMULATION STUDIES

Multi-particle simulations in 6 dimensional space were done. The stripping foil is defined as an rectangle in (r, y), and particles are injected only when it is inside the foil (Fig. 4). For a circulating particle, it is affected the scattering and energy loss when it hits the foil. The particle which exceeds the vertical aperture was lost.

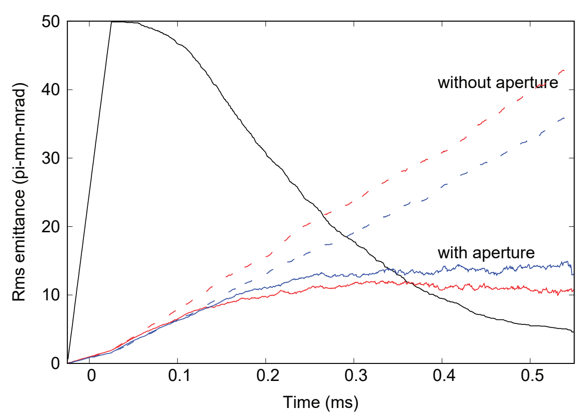

Figure 5: Horizontal (red) and vertical (blue) emittance growth caused by foil scattering. Number of survived particles is plotted in black (full-span=100%). Dashed lines shows the case with infinitely large foil.

Emittance Growth without Acceleration

First, free emittance growth caused by the scattering is simulated without acceleration. Constant frequency rf was applied to keep the beam energy. The result showed that the transverse emittances were linearly increased at constant speed of 70 πmm-mrad/ms, as Fig. 5, and the speed was independent from the initial distribution. Significant beam loss at vertical aperture was started around 0.1 ms, which corresponds to 150 turns, and 90 % of the beam was lost within 0.5 ms.

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With Acceleration

With acceleration, the synchronous particle orbit is shifted at the speed of 50 mm/ms. Therefore a particle continues hitting the foil for 0.2 ms in the average. This time is comparable to the emittance growth, as shown in Fig. 5. Simulation studies were done with acceleration. Injected beam is assumed to be matched with the ring. Figure 6 shows the simulated emittance growth and beam loss. Capture efficiency was 25.7%. Each captured particle hits the foil 200 - 500 times.

Dependence on the momentum spread of the injected beam have been studied (Fig. 8). The capture efficiency was reduced to 9% by increasing the momentum spread up to 1%.

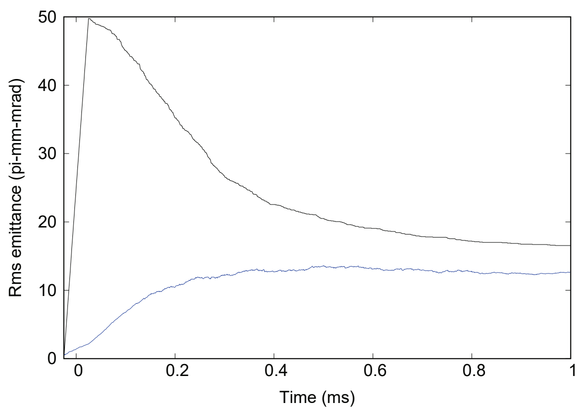

Figure 6: Vertical emittance growth (blue) and number of survived particles (black, full-span = 100%).

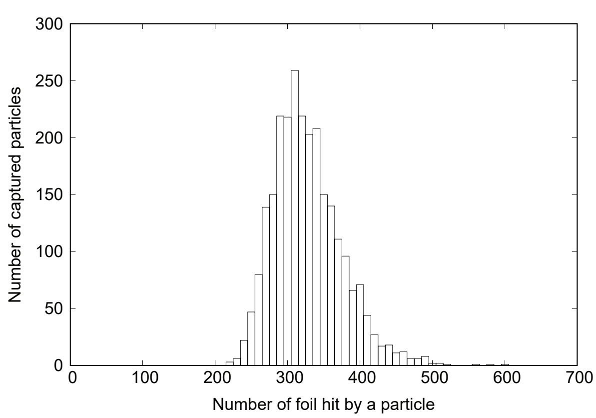

Figure 7: Histogram of number of foil hitting by a captured particle.

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. However the efficiency is still higher than the experimental results. Further studies, including experiments, are necessary such as injection mismatches.

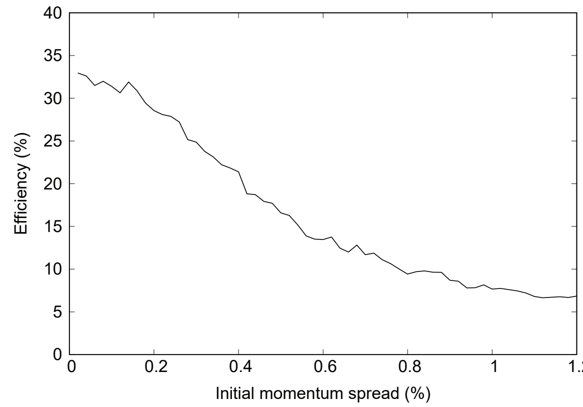

Figure 8: Capture efficiency depending on initial momentum spread.

Unfortunately, the FFAG accelerator is down since the winter of 2015, because of a trouble of injecter linac. It will be recovered in this Summer. Also, installation of another rf cavity is planned in order to increase the accelerating voltage. It will reduce the beam loss at the injection.

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