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ADIABATIC CAPTURE IN THE FETS-FFA RING

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Abstract

Adiabatic capture of a coasting beam can be used to minimise the emittance of the resulting bunched beam – for example to capture the injected beam at the start of the acceleration cycle. In some cases, the voltage follows the so-called iso-adiabatic voltage law in order maintain the same adiabaticity throughout capture. Here we show that a linear evolution can result in a smaller final emittance than an iso-adiabatic scheme. This is shown by tracking a distribution through various capture schemes, taking as our example capture at injection in the FETS-FFA proton ring. We include preliminary results on the effects of longitudinal space charge which can be significant in this ring.

INTRODUCTION

Future high-power neutron spallation sources need to deliver more neutrons while meeting sustainability targets and ensuring flexible operation. Fixed Field Accelerators (FFAs) are a promising solution, as they can achieve high repetition and reduced energy consumption with DC magnets, and stack beams to flexibly vary repetition rates while maintaining high peak current. A horizontal FFA consisting of FD doublet spiral magnets is currently under study at ISIS. A 12 MeV prototype ring known as the FETS-FFA will first be constructed as a proof of principle (named for its injector, the Front End Test stand). The specific topic of adiabatic capture at injection in the prototype ring is the subject of this paper - a study of the lattice [1], the magnet design [2] and space charge simulations [3] are also presented in these proceedings.

INJECTION SCENARIOS

The FETS injector provides a 3MeV H^- beam with momentum spread $dp/p = \pm 0.004$ and bunch duration 350 ns (assuming the installation of debunching cavity and modification of the chopper power supply). Injection is via charge exchange through a foil. Two RF capture scenarios are considered

- Injection of a bunched beam into a stationary bucket.
- Adiabatic capture of a coasting beam.

In the case of bunched beam injection, the RF voltage is set sufficiently high to ensure that, once the beam has completed a synchrotron oscillation and filled a Hamiltonian contour, the emittance is no more than 75% of the bucket area. At low intensities, when longitudinal space charge can be neglected, the RF voltage required is 5 kV. At maximum intensity when 3×10^{11} particles are injected and space is significant, the RF voltage needs to be increased to 6 kV to compensate for bucket area reduction. Once injection has been completed, the synchronous phase is increased linearly and then kept at a constant value for most of the cycle until it is returned to zero once the extraction energy is reached. To be consistent with operation at 100 Hz, acceleration should be completed within 8 ms (allowing 2 ms for recovery of the RF).

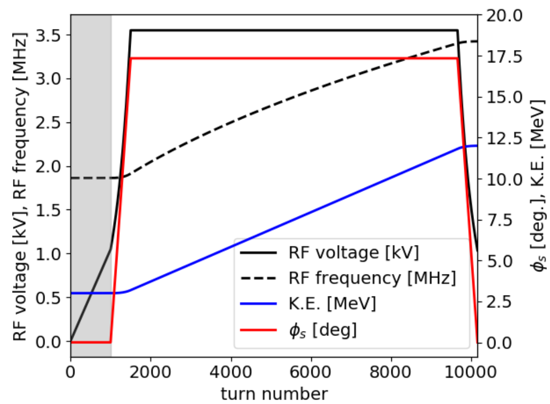

Figure 1: RF voltage (black solid) and frequency (black dash) program for the case of adiabatic capture with linear voltage ramp from zero volts. The corresponding kinetic energy (blue) and synchronous phase (red) evolutions are also shown. The period of adiabatic capture is shaded.

On the other hand, in the case of adiabatic capture, a coasting beam is injected until the desired intensity is reached. The voltage is then increased until the beam is fully captured in a stationary bucket (shaded region in Fig. 1). In the ideal case, the longitudinal emittance of the final bunched beam will be equal to the emittance of the coasting beam. This scheme is considered for the prototype ring as it would allow a beam with longer duration to be injected (note: the minimum injected bunch duration that can be injected without modifying the chopper power supply is 450ns). Adiabatic capture can also result in a lower longitudinal emittance after capture compared to the case of bunched beam capture. However, adiabatic capture is typically much slower than bunched beam capture since it needs to be on a timescale significantly longer than a synchrotron period.

ADIABATIC CAPTURE

We use the term *adiabatic capture* here to refer to any voltage law that minimises, or ideally entirely avoids, any increase in emittance during the capture of a coasting beam. In Hamiltonian dynamics, an adiabatic variation requires that the synchrotron frequency change slowly over the course of a single synchrotron period. This is characterised by the

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Table 1: RF parameters for the case of adiabatic capture in 1000 turns in the case of low and high intensity. The low intensity parameters correspond to Fig. 1.

Intensity	0	3e11
Harmonic number	2	2
RF voltage for capture [kV]	1.045	2.99
Maximum RF voltage [kV]	3.5	6.01
RF frequency at injection [MHz]	1.86	1.86
RF frequency at extraction [MHz]	3.42	3.42
Max ϕ_s [deg]	17.4	10.1
Number of turns [1000s]	10.2	10.2
Acceleration time [ms]	8	8

adiabaticity parameter α given by [4]

$$\alpha = 2\pi \frac{1}{\omega_s^2} \frac{d\omega_s}{dt} \tag{1}$$

The greater the value of α, the less adiabatic the process. Noting that $\omega_s \propto \sqrt{U}$ and rearranging the above, the *iso-adiabatic* voltage law $U_{iso}(t)$ [5] follows

$$U_{iso}(t) = \frac{U_1}{\left(1 - \frac{t}{t_c}\frac{\sqrt{U_2}-\sqrt{U_1}}{\sqrt{U_1}}\right)^2} \tag{2}$$

where t_c is the capture time and U_1, U_2 are the RF voltages before and after capture, respectively (note: U_1 needs to be finite). It should be noted that a more generalised set of voltage laws has recently been studied by Koscielniak [6, 7].

Previous studies have generally found that the iso-adiabatic voltage law does better than alternatives in minimising the captured bunch emittance [5, 8, 9]. A counter example is found in [10] where they find a linear voltage ramp suffices and is preferable from the point of view of practical implementation. Here we report a case where the linear voltage law does better than the iso-adiabatic case.

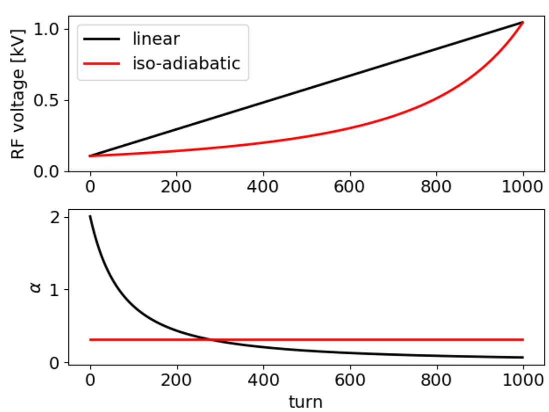

Figure 2: RF voltage evolution (top) in the case of a linear (black) and iso-adiabatic (red) voltage law and (bottom) the corresponding adiabaticity parameter α for the two cases. In both cases $U1 = 0.1045$ kV and $U_2 = 1.045$ kV.

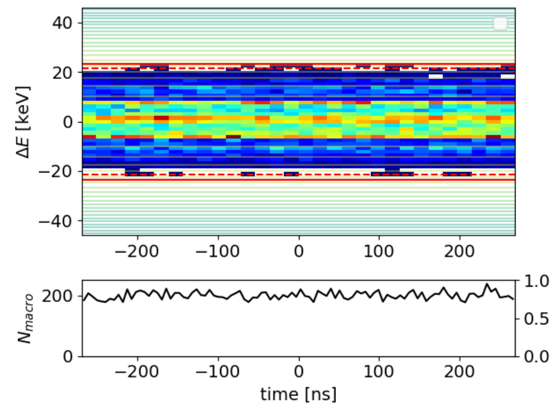

Figure 3: Coasting beam distribution before the start of capture in terms of longitudinal phase space (top) and line density in terms of macroparticles per time bin (bottom). The red dash and red solid lines correspond to the 99.9% emittance and 100% emittance, respectively. The line density variation is a statistical artifact.

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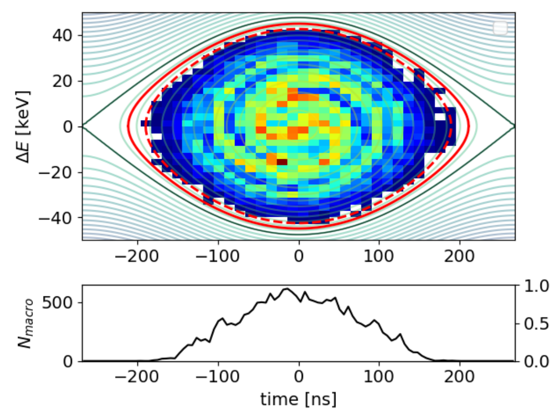

Figure 4: Beam distribution at the end of capture in the case of a linear voltage ramp from zero volts. The red dash and red solid contours correspond to the 99.9% emittance and 100% emittance, respectively. Space charge is not included.

The simulation starts with a coasting beam uniformly distributed in phase and with a 100% momentum spread of dp/p = ±0.004 (Fig. 3). The corresponds to a total emittance of 0.05Vs. We aim to capture this distribution in a stationary RF bucket with area 0.065 Vs. To create this bucket area the RF voltage at the end of capture $U_2 = 1.045$ kV. Tracking of 20k macroparticles is carried out in PyHEADTAIL [11, 12]. A capture duration of 1000 turns is found to be a good compromise between avoiding a large increase in emittance and fitting within the available acceleration time (8 ms). At the end of capture, the final emittance is given by the area of the Hamiltonian contour that encloses all the particles (we also note the 99.9% emittance). Note that longitudinal space charge is not included in these simulations.

Typical voltage laws are shown in Fig. 2 along with the corresponding adiabaticity evolution. The final captured

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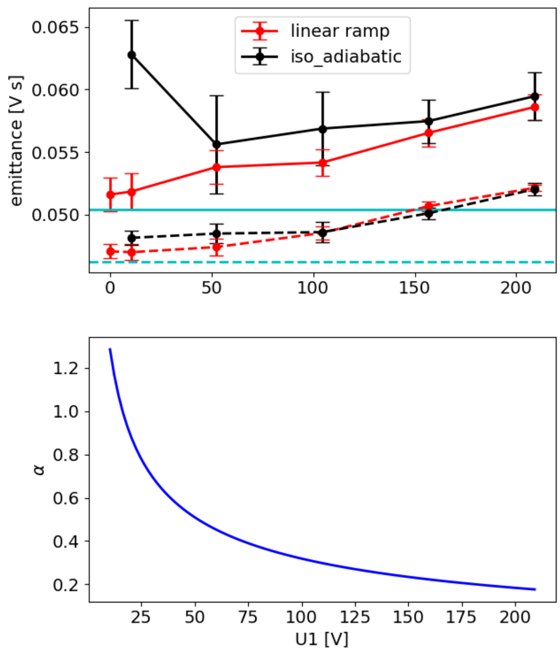

Figure 5: Top: Emittance after capture as a function the initial voltage U_1 when the final voltage is fixed, $U_2 = 1.045$ kV and the number of capture turns is 1000. The 100% emittance (solid lines) and 99.9% emittance (dashed lines) are shown for the iso-adiabatic (black) and linear (ramp) cases. The horizontal lines show the 100% (solid) and 99.9% (dashed) coasting beam emittances . Bottom: The adiabaticity α as a function of U_1 for the iso-adiabatic case.

beam distribution is shown in Fig.4 for the case of a linear increase of RF voltage from 0.1045 kV to 1.045 kV. Figure 5 shows the variation of emittance with initial voltage U_1 for the case of iso-adiabatic and linear voltage laws with fixed U_2 and ramp turns. For each U_1, the tracking was repeated for a set of 30 random distributions. The points in the figure show the mean and the error bars the standard deviation for each set. The error bars are larger in the 100% emittance case compared with the 99.9% emittance case because of the relatively small number of particles at the edge of the distribution.

It is clear from Fig. 5 that the lowest 100% emittance is obtained if the voltage is ramped linearly from zero volts. On the other hand, in the iso-adiabatic case, the emittance is at its highest level for the lowest value of U_1 tested - this is to be expected the since α increases as U_1 is reduced. The increase in the mean 100% emittance when $U_1 > 50$ V is not consistent with the fact that α is decreasing at the same time. This may be because the instantaneous, non-adiabatic rise of the voltage to U_1 at the start of tracking is not accounted for in the α parameter (the same argument applies to the linear ramp case). Note, when $U_1 = 250$ V, the bucket height is approximately equal to the coasting beam energy spread.

To reduce the effect of the instantaneous voltage rise, U_1 needs to be fixed to a low value. The value of α for the iso-adiabatic case can be reduced either by lowering the final capture voltage U_2 or by increasing the number of capture turns. However, the lowest value of U_2 is limited by the required bucket area while the number of capture turns is constrained by the available acceleration time. Another approach, that requires further investigation, is to increase the voltage more gradually until it reaches U_1 instead of switching it on instantly.

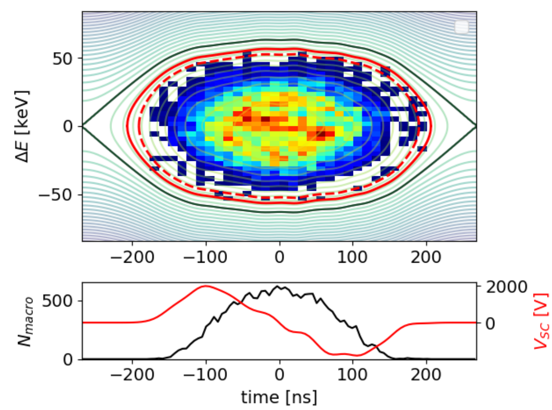

Figure 6: Beam distribution at the end of capture with space charge included. The voltage ramp is linear from zero. The separatrix includes the effect of space charge which is shown in the lower panel (red line).

Since this is a high intensity ring, longitudinal space charge must be considered. This has the effect of the reducing the bucket area. At the highest intensity, when 3e11 particles are injected, the capture voltage is increased to 3 kV in order to compensate this reduction. Figure 6 shows an example distribution at the end of capture. The maximum voltage during the acceleration cycle is also higher (see Tab. 1, right column) but within the specification of the RF cavity.

CONCLUSION

Adiabatic capture is investigated as an alternative to direct capture in a stationary bucket for case of the FETS-FFA ring. It was found that ramping the voltage linearly from zero resulted in the lowest captured beam emittance when compared with following the iso-adiabatic voltage law. A bilinear voltage law, i.e. a fast linear increase followed by a slower linear increase, was also studied but the results are not included here. Adiabatic capture can also be done at the intensity limit by increasing the RF voltage to compensate the longitudinal space charge. Although we looked at injection in this paper, the results are relevant for beam stacking as well in which case a beam coasting at the extraction energy needs to be captured. The effect of coasting beam instabilities, and how they can be damped in a zero-chromaticity ring such as this, requires investigation for the ISIS2 case.

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