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LONGITUDINAL DYNAMICS IN THE PROTOTYPE vFFA RING FOR ISIS2

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Abstract

A vertical Fixed Field Accelerator (vFFA) is a candidate for a future high-power (MW-class) spallation source at ISIS. In order to assess the feasibility of this novel ring, a prototype is currently being designed. Here we consider the longitudinal dynamics in the prototype ring. A key requirement of future neutron spallation sources is flexibility of operation to best serve multiple target stations. Beam stacking allows a rapid cycling, high intensity machine to operate at lower repetition rates but with higher peak output. Here we show how beam stacking can be realised in the vFFA while minimising the peak RF voltage required.

INTRODUCTION

The next generation of high power neutron spallation sources will need to push to ever higher beam powers while at the same time incorporate, at the heart of their designs, features that allow sustainable and flexible operation. FFAs meet all three requirements - DC magnets allow high repetition rates and so high beam power, the use of DC superconducting magnets may reduce energy consumption considerably compared to AC magnets and, finally, the use of beam stacking facilitates flexible operation by allowing the repetition rate seen by target stations to be varied while maintaining high peak current.

A scaling vFFA design for a future neutron spallation source, an upgrade to ISIS, is under consideration alongside RCS and accumulator ring options. In the vFFA, the beam moves vertically as it is being accelerated, i.e. the dispersion is non-zero only in the vertical plane [1, 2]. The beam is accelerated in a moving bucket, just like a synchrotron. However, since the path length is independent of momentum, the momentum compaction factor is zero, just like in a linac.

Since this is a novel accelerator type, the design of a 12 MeV, prototype vFFA ring is being pursued. The ring will use the 3 MeV, H^- Front End Test Stand (FETS) as an injector. One of the key aims of the prototype will be to demonstrate beam stacking. Details of the design methodology and the status of the FETS-FFA ring study are reported in [3, 4].

ACCELERATION

During the injection process, the beam is captured in a stationary bucket with sufficient voltage to ensure a bucket fill factor of ~ 75%. This is depicted in Fig. 1 (top) where the area within the red contour, containing 99.9% of particles, corresponds to this fill factor.

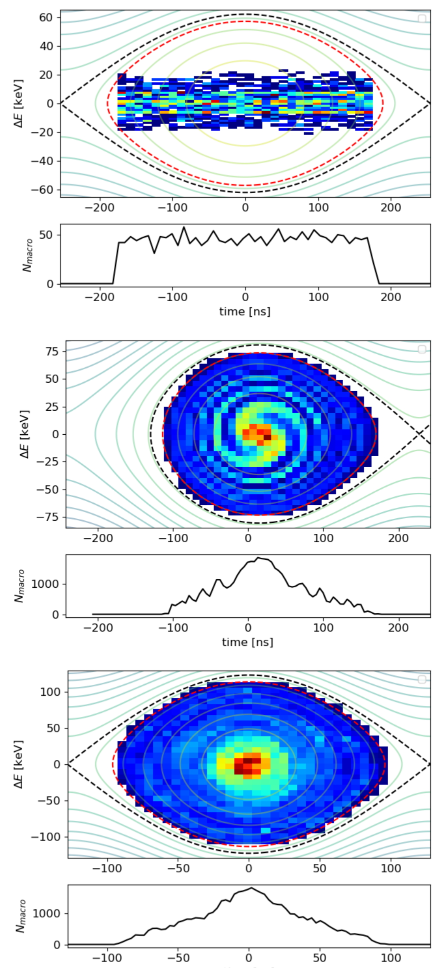

Figure 1: Phase space distributions calculated by PyHEADTAIL (from the top): at the first injection turn, at turn 1000 when ϕ_s reaches a maximum and at extraction. In the upper subfigures, the black contour is the separatrix and the red contour contains 99.9% of particles. The lower subfigures show the time projection histogram.

Assuming the nominal setup, the beam from the FETS injector has a minimum duration of 400 ns and full momentum spread, $dp/p = \pm 0.006$. In order to relax the RF requirements, it is proposed that both the duration and momentum

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spread are reduced to 350 ns and $dp/p = \pm 0.004$ - the former by modifying the FETS chopper power supply and the latter by installing a debunching cavity in the beam transfer line to the FFA ring.

Contrary to the synchrotron case, there is no bending field variation in a FFA for the synchronous phase to follow. This allows great flexibility in the RF program. Acceleration proceeds by sweeping the synchronous phase to some constant value ϕ_s^{max} in as few turns as possible while, at the same time, ensuring there is no emittance increase owing to non-adiabatic variation of longitudinal parameters. With a synchrotron period of approximately 100 turns, a phase sweep of 1000 turns is found to be sufficiently slow to meet this condition. The reverse process occurs in the final 1000 turns in order to store the beam in a stationary bucket at the extraction energy. The bucket area is kept constant during the entire acceleration cycle.

The number of turns maintained at the synchronous phase ϕ_s^{max}, as well as the value of the phase itself, are determined by an optimiser whose goal is to achieve the desired extraction energy within the allowed acceleration time (8 ms, to be consistent with 100 Hz operation). After imposing the constraint that the bucket area is constant for the entire acceleration cycle, the turn-by-turn voltage may be calculated. The resulting RF program is shown in Fig. 2 and the main parameters listed in Table 1. In order to extract the beam from the same vertical elevation for a range of tunes, acceleration up to 17 MeV is envisaged.

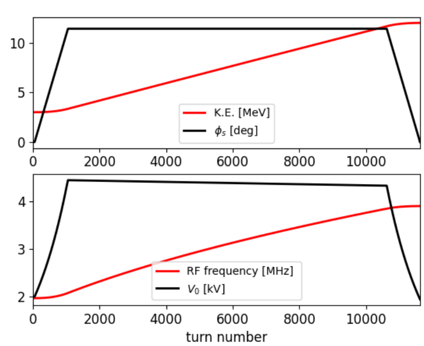

Figure 2: The RF program for acceleration to 12 MeV. The upper figure shows the synchronous phase as a function of turn and the resulting kinetic energy evolution. In the lower figure the corresponding RF voltage and frequency pattern is shown. Acceleration is completed in 8 ms.

The results of PyHEADTAIL [5,6] longitudinal tracking simulations are shown in Fig. 1. The growth of the longitudinal emittance is insignificant indicating that the variation in RF parameters is adiabatic.

STACKING

A number of features of FFA machines facilitate beam stacking:

Table 1: RF Parameters for Acceleration in the Nominal Case (12 MeV) and at the Limit of the Tune Range (17 MeV)

Extraction energy [MeV]	12	17
Harmonic number	2	2
RF voltage at injection [kV]	2	2
Maximum RF voltage [kV]	4.5	5.2
RF frequency at injection [MHz]	1.9	1.9
RF frequency at extraction [MHz]	3.8	4.5
Max ϕ_s [deg]	11.4	13.6
Number of turns [1000s]	11.6	13.1

- The zero chromaticity of scaling FFAs avoids the tune variation arising from the momentum spread of the stacked beam.
- The dispersive spread of the beam is naturally accommodated in the aperture.
- The flexibility of the RF system allows the stacking process to optimised.

Stacking allows the repetition rate seen by the neutron target to be reduced while maintaining high intensity. In ISIS2 it is envisaged that this repetition rate could be varied in the range 10-100 Hz by stacking up to 10 beams. It is planned that the FETS vFFA ring will demonstrate stacking of up to 5 beams.

The stacking process begins by accelerating the first beam up to the desired energy and allowing it to adiabatically debunch. Phase displacement, a consequence of Liouville's theorem, means that it is not possible to stack one beam on top of another in longitudinal phase space. This is because the accelerating bucket, with bucket area A, displaces the surrounding phase space resulting in a reduction in the mean energy of the circulating beam according to

$$E_{displ} = \frac{\omega_0 A}{2\pi}, \quad (1)$$

where ω_0 is the revolution frequency.

It is also important, when choosing the stacking energy, to consider the effect of the accelerating RF on the already circulating, stacked beam. This can occur if there is a rational relation between the rf frequency ω_{rf} and the revolution frequency of the stacked beam ω_0 (the so-called sub-harmonic effect [7]). For example, if the beam is stacked at the 12 MeV extraction energy, where revolution frequency is twice that at injection, then the harmonic 2 RF used to capture newly injected beam creates a harmonic 1 stationary bucket at the stacked beam energy. In that case, a fraction of the stacked beam will be unintentionally captured and accelerated by the RF.

Instead, we choose to stack at 4.8 MeV. This energy is chosen to avoid these sub-harmonic effects and because it is the energy at which the fractional increase of relativistic beta is equal to that of ISIS2. The RF program to stack a single

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beam is shown in Fig. 3. The initial RF program follows the same pattern as in the standard acceleration case. However, in this case the number of turns at which the synchronous phase is fixed at ϕ_s^{max} is reduced so that the beam is accelerated to a lower energy. Once acceleration is complete, the voltage is reduced to zero while stationary bucket conditions are maintained. In this way the beam is adiabatically debunched, minimising the energy spread of the resulting coasting beam. PyHEADTAIL simulations show that debunching is adiabatic if the voltage is reduced in 1000 turns or more. In Fig. 3, the point where adiabatic debunching begins is indicated.

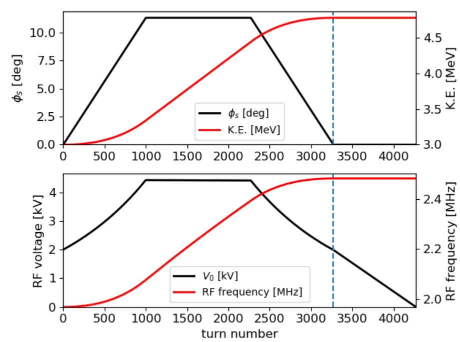

Figure 3: The RF program to accelerate and stack a single beam. The vertical line shows the point at which adiabatic debunching begins.

Additional bunches are then stacked such that, once they are debunched and coasting, they do not overlap already coasting beams in terms of energy. This is done by adjusting the RF program of each injected bunch so that they are stacked at an energy below the previous bunch. The energy separation between bunches is given by half the sum of E_{displ} Eq. (1) evaluated at the reference energy of each beam.

Two options are considered for the capture RF - fixed frequency sinusoid RF and barrier bucket RF. While the former is most efficient in terms of the RF voltage required, barrier bucket RF has two advantages - the flexibility of the barrier bucket waveform allows the beam to be stacked at a range of energies and, secondly, the reduction in the peak line density (i.e. the increased bunching factor) results in a reduction in transverse space charge [8] .

Figure 4 shows how the coasting beam is adiabatically captured by linearly increasing the amplitude of the barrier bucket waveform (shown in Fig. 5) from zero to 42 kV in 1000 turns. This voltage is sufficient to create a beam-free time of 200 ns to allow for the extraction kicker rise time. The RF voltage can be reduced by increasing the pulse duration (T_1 in Fig. 5). to ensure the same integrated signal.

SUMMARY

The RF requirements for acceleration and beam stacking have been established for the FETS-FFA ring. A scheme to stack the beam, that takes account of sub-harmonic effects and phase displacement is described.

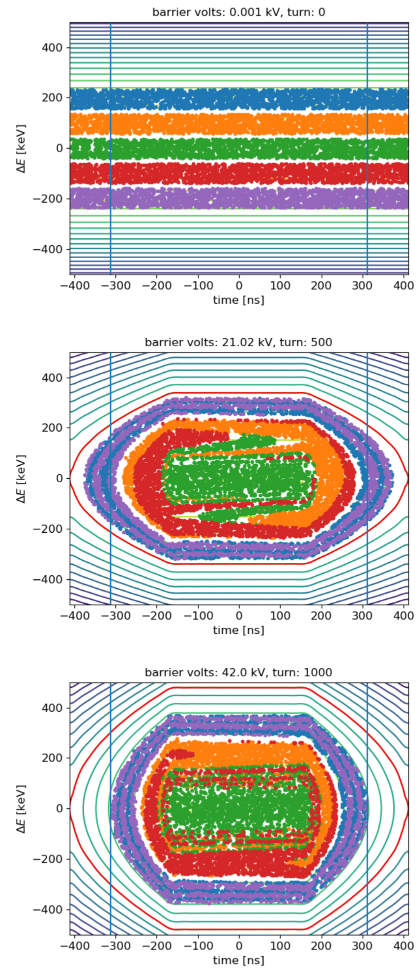

Figure 4: Capture process as tracked by PyHEADTAIL. The barrier bucket amplitude is linearly ramped from zero to 42 kV in 1000 turns. The vertical blue lines show the desired 200 ns gap time.

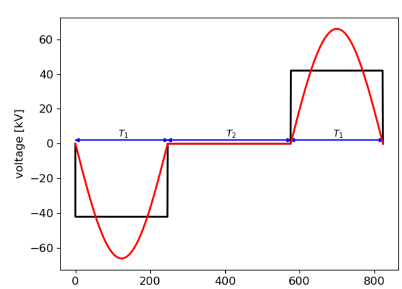

Figure 5: Rectangular and half-sinusoid barrier bucket waveforms. Both waveforms have the same integrated voltage over half a wavelength. It is convenient to label the barrier pulse duration T_1 and the gap between pulses T_2.

In order to reduce the transverse space charge and to maximise stacking flexibility, barrier bucket RF is preferred to capture the stacked beam.

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