FREQUENCY MODULATED CAPTURE OF COOLED COASTING ION BEAMS

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Abstract

Transverse space charge effects in the Low Energy Ion Ring (LEIR) at CERN have been shown to be a major source of particle losses, which can be mitigated with a larger RMS longitudinal emittance. However, due to electron cooling during the injection plateau, the longitudinal density is very high prior to RF capture. In addition there is an uncontrolled cycle to cycle variation in the revolution frequency of the coasting beam on the flat bottom, which degrades the beam quality at capture. In this paper we show that applying an RF frequency modulation during the capture process allows both a controlled blow-up of the longitudinal emittance and a very good reproducibility in the longitudinal distribution, which in turn improves beam transmission through the machine.

INTRODUCTION

The Low Energy Ion Ring (LEIR) is the first synchrotron in the ion injection chain for the Large Hadron Collider (LHC). The high intensity LEIR cycle has a long flat bottom with sequential injections from Linac3, after each injection the new beam is electron cooled and added to the stack prior to the next injection. Low intensity beams with a single injection are also used, but they are not discussed in this paper. The cooled coasting beam is captured adiabatically in harmonic $h = 2$, with $h = 4$ in bunch lengthening mode, prior to acceleration.

At present there is a variation on the revolution frequency of the stacked beam from cycle to cycle, which appears to be partly due to the electron cooling. As the RF frequency used for capture is the same cycle to cycle, but the beam revolution frequency is not, the phase space distribution of the captured beam becomes non-reproducible.

Losses shortly after capture and during the early part of acceleration have been shown to be partly caused by transverse space charge effects [1]. Larger longitudinal emittances reduce the transverse space charge effects, and therefore minimise the losses. An intentional offset between the revolution frequency and RF frequency has previously been used to achieve this, however it suffers from poor reproducibility. A reproducible method of increasing the captured emittance is desirable to allow more reliable high intensity beams to be produced.

FREQUENCY MODULATION

The electron cooling has two significant consequences in LEIR. First, the strong cooling required to compensate transverse effects and maximise transmission leads to longitudinal phase space density that is too high for optimum transmission after RF capture. Second, through interactions between the beam and the e-cooler the revolution frequency

of the coasting beam has slight variability from shot to shot, which impacts the reproducibility of capture.

By applying frequency modulation to the RF during capture both of these effects can be mitigated, whilst maintaining strong cooling on the flat bottom. Without a modulation the RF frequency during capture is set to $f_{rf} = hf_{rev}$, where h is the harmonic number and f_{rev} is the design revolution frequency. To apply the modulation this is modified to

$$f_{rf} = h\left[f_{rev} + \Delta f(t)\right], \tag{1}$$

where $\Delta f(t)$ is a time dependent offset used to modulate the RF frequency. $\Delta f(t)$ given by

$$\Delta f = A(t) \times \sin\left(\int 2\pi f_{mod}(t)dt\right), \tag{2}$$

where $A(t)$ is a time dependent amplitude function used to decrease the amplitude as the voltage increases and $f_{mod}(t)$ is a time dependent frequency function used to follow the changing synchrotron frequency during capture. Rather than $A(t)$ being a linear function it is preferable to maintain high amplitude whilst at low voltage and then ramp down quickly towards the end of capture. It has been found empirically that a good result is given by

$$A(t) = A_{max} \times \left[1 - e^{R(t)-R_0}\right], \tag{3}$$

where A_{max} is the maximum modulation amplitude, and $R(t)$ is a linear function in the range $[0, R_0]$. Figure 1 shows the capture voltage in red, and a Δf with $f_{mod} = [50, 675]\,\text{Hz}$, $A_{max} = 625\,\text{Hz}$, and $R_0 = 10$ in blue. Combining frequency modulation with a voltage ramp means particles are captured by the bucket as it passes through the coasting beam and distributed uniformly within, giving a reproducible almost waterbag distribution.
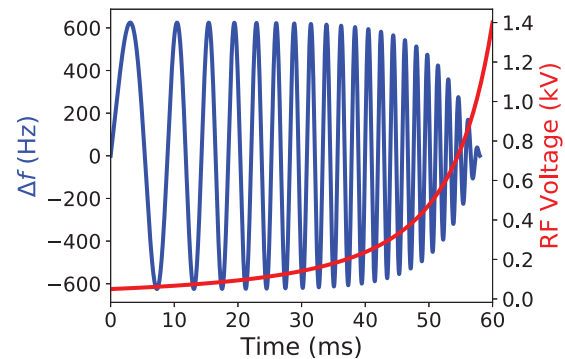

Figure 1: An example of the Δf (blue) and adiabatic voltage function (red) used to capture the beam with modulated RF frequency, with a revolution frequency of 0.35 MHz.
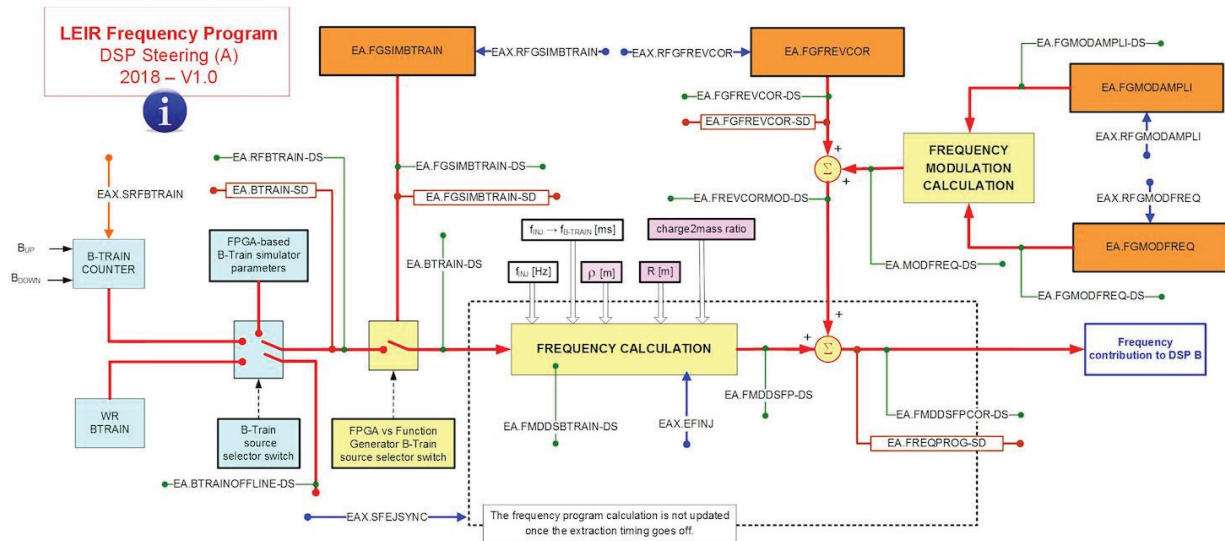
Figure 2: Diagramatic representation of the RF frequency calculation implemented in the LEIR low-level RF, the newly implemented functions can be seen in the top right corner.

LLRF IMPLEMENTATION

The LEIR LLRF was upgraded in 2016 to the second generation LLRF family already successfully deployed in other CERN machines [2]. This allowed an increase of the bandwidth of the beam loops as well as controlling the two LEIR cavities in parallel. Figure 2 shows a synoptic description of the revolution frequency calculation. The block labeled "FREQUENCY CALCULATION" computes the design revolution frequency of the beam based on the measured magnetic field and machine parameters; bending radius (ρ), average radius (R), and charge to mass ratio $\left(\frac{q}{m}\right)$.

To compensate for small offsets in the revolution frequency of the coasting beam after cooling, there is a Δf function ("EA.FGFREVCOR"), which is used to provide an offset to the calculated revolution frequency. The first implementations of frequency modulated capture used this function programmed with a LabVIEW application, however this was not easily integrated with the operational environment and so a new approach was requested.

For the 2018 Pb run, the low-level RF was modified with two new functions named "EA.FGMODAMPLI" and "EA.FGMODFREQ", which are used to set $A(t)$ and $f_{mod}(t)$ respectively for the calculation of Δf in Eq. (2). Separating the frequency modulation from the frequency offset in this way greatly simplifies the requirements on operations, as an optimal modulation can be set by an expert and in case of a drift on revolution frequency the operators need only to modify the offset. The modulation calculation is implemented in a DSP with the following code block, which runs each tick of the low-level RF system:

```
rad_now = 2.0*DSP_PI*FGmodfreq*deltaT_s
          + rad_prev;
ModFreq_Hz = FGmodampli * sinf(rad_now);
FrevCorMod_Hz = FGfrevcor + ModFreq_Hz;
rad_prev = rad_now;
```

The variables rad_now and rad_prev are used to give a numerical integration in place of the $\int 2\pi f_{mod}(t)dt$ term in Eq. (2), FGmodfreq and FGmodampli are the values of the "EA.FGMODAMPLI" and "EA.FGMODFREQ" functions sampled each tick, deltaT_s is the time between ticks of the low-level RF clock (12.5 µs), FGfrevcor is the sampled value of "EA.FGFREVCOR" and FrevCorMod_Hz is the final Δf that is added to the computed revolution frequency.

SIMULATIONS AND MEASUREMENTS

Simulations were performed with the longitudinal tracking code BLonD [3], to demonstrate the effect of RF frequency modulation. Three coasting beams of Pb_{208}^{54+} were generated with a parabolic energy distribution, with a half height of 1 MeV and mean $dE = -0.75$ MeV, 0 MeV, 0.75 MeV. The RF voltage was applied on h=2 and h=4 with $V_{h=2}$ equal to the voltage function in Fig. 1 and $V_{h=4} = 1.1 \times V_{h_2}$. Two sets of simulations were run, the first with no frequency modulation and the second with Δf_{rf} as shown in Fig. 1.

The results of the six simulations given in Fig. 3 clearly show that by adding frequency modulation the beam profile is less dependant on energy offset and has a larger longitudinal emittance than with a fixed frequency. There is some residual structure visible with modulation (dashed lines), however in measurements this effect is smaller and is rapidly filamented out with no apparent negative consequences.

After applying the modulation in operation the beam was measured after capture. Figure 4 shows the phase space reconstructed through longitudinal phase space tomography [4], which shows the very uniform distribution with only a small amount of residual structure. By varying the modulation amplitude the final emittance can be readily and reproducibly varied, which allows the longitudinal emittance

MC4: Hadron Accelerators

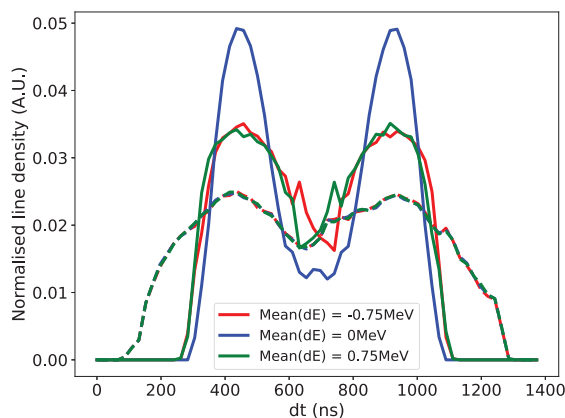**T12 Beam Injection/Extraction and Transport**

Figure 3: Simulated line density with (dashed) and without (solid) RF frequency modulation during capture of coasting beams with mean energy offsets -0.75 (red), 0 (blue) and 0.75 (green) MeV.

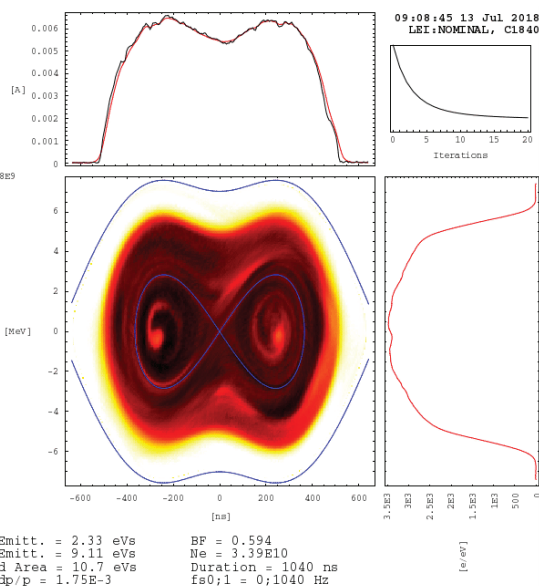to be tuned more easily and accurately than previously possible.

Figure 4: Tomographic reconstruction of longitudinal phase space at the end of capture with RF frequency modulation.

For LEIR the main figure of merit is the extracted intensity. A comparison of standard fixed frequency capture with the new modulated frequency capture was run over a few days to allow comparison under normal operating conditions. Figure 5 shows the stacked and extracted intensities with modulated frequency and fixed frequency capture, it can be clearly seen that both the reproducibility and the absolute value of transmission are significantly improved.

CONCLUSION

A novel approach to capturing coasting ion beams has been developed for use in the Low Energy Ion Ring (LEIR)
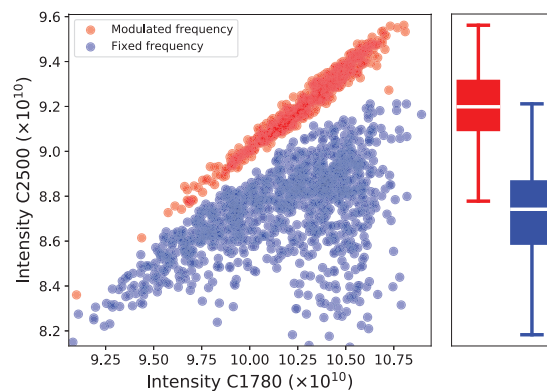

Figure 5: Comparison of the intensity prior to capture at 1.78 s after cycle start (C1780) with the intensity 2.5 s after cycle start (C2500) with fixed frequency (blue) and modulated capture (red). The right hand pane shows boxplots of the distributions at C2500.

at CERN. By modulating the RF frequency during an adiabatic capture process it is possible to distribute the beam very uniformly over the bucket with very little shot to shot variation. This has the effect of improving both the reproducibility and absolute value of transmission through the machine. After initial demonstration of the effectiveness with a LabVIEW application, the low-level RF was modified to allow the relevant parameters to be set in a way that is more suitable for operation and separates the correction for variation in revolution frequency from the optimisation of capture modulation.

ACKNOWLEDGEMENTS

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