

# ENERGY DEPENDENCE OF THE REPRODUCIBILITY AND INJECTION EFFICIENCY OF THE LINAC3-LEIR COMPLEX

S. Hirllaender\*, H. Bartosik, G. Bellodi, N. Biancacci, V. Kain, A. Saa Hernandez, R. Scrivens  
CERN, Geneva, Switzerland

## Abstract

High intensities in the CERN Low Energy Ion Ring (LEIR) are achieved by stacking several multi-turn injections from the pre-accelerator LINAC3. Up to seven consecutive 200  $\mu$ s long, 200 ms spaced pulses are injected from LINAC3 into LEIR. An inclined septum magnet combined with a collapsing horizontal orbit bump allows a 6-D phase space painting via a linearly ramped mean momentum along the LINAC3 pulse and injection at high dispersion. The injected energy distribution measured by the LEIR longitudinal Schottky is correlated with the obtained injection efficiency in this paper. Studies in 2018 revealed that the achievable accumulated intensity of LEIR strongly depends on the longitudinal distribution from LINAC3, which does not stay constant. This paper summarises the experimental results and means to further improve reproducibility and high injection efficiency.

## INTRODUCTION

The injection process from LINAC3 into LEIR is complex and consequently sensitive to small changes in the initial conditions. From LINAC3 a 200  $\mu$ s long pulse, which is ramped in energy, is transported through the transfer line to LEIR. At injection into LEIR, the ramped pulse meets a collapsing horizontal orbit bump at a region of high dispersion of 10 m. The pulse is injected over 70 turns, and the collapsing bump compensates the dispersive displacement due to the energy swing along the pulse. Consequently, the incoming pulse is not displaced while the already circulating beam is removed from the injection region. After 200 ms the next pulse is injected in the same manner, while the circulating beam is cooled and dragged by the electron cooler longitudinally to free space for the next injection. This procedure is repeated seven times, while the circulating beam gains intensity. The LEIR stacked multi-turn injection was found to be very sensitive to changes in the energy distribution delivered by LINAC3. Small energy changes lead to reduced injection efficiency. The reduced accumulated intensity modifies the cooling properties, which further reduces the stacked intensity. Detecting and correcting energy changes became hence an important study topic for stabilising LEIR performance.

The paper presents methods to measure and correct LINAC3 energy drifts parasitically. The presented insights were gained and applied during the Pb ion run 2018 yielding the best performance in LEIR's history in terms of intensity and reproducibility.

\* simon.hirllaender@cern.ch

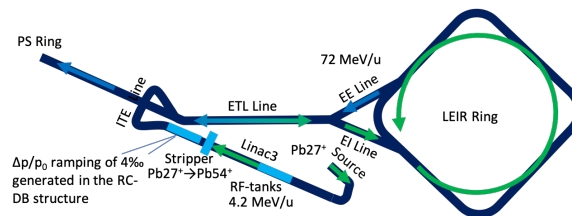


Figure 1: An overview of the LINAC3-LEIR Complex. The ramping-debunching cavity is responsible for the energy ramping of the 200  $\mu$ s long pulse arriving at LEIR.

## THE DIAGNOSTICS

The LEIR longitudinal Schottky system is used to measure the beam momentum distribution [1]. The Schottky spectra were treated in control room graphical user interfaces in both JAVA and Python. Various key parameters can be derived from the spectra. Examples are the injected mean beam energy and distribution as well as cooling times and dragging parameters. Data smoothing and averaging has to be applied to obtain reliable measurements for these key parameters. The design energy distribution is ramped in a range of  $\pm 2\%$  around  $4.2 \text{ MeV u}^{-1}$  [2].

The measurement of the initial distribution is further improvement by disabling electron cooling on the measurement cycle with one injection. This is also true for the pair of ramping and debunching cavities at the end of LINAC3 (Fig. 1) whose purpose is to introduce the energy ramp along the LINAC3 pulse. The ramping is set to a constant value, typically the mean value of the operational ramp.

### Zero-Crossing Constant Energy Distribution

The ramping and debunching cavities amplitudes and phases determine the final convoluted energy distribution and can be set up exploiting the longitudinal Schottky with the measurement cycle as mentioned above. The zero-crossing point needs to be evaluated. It corresponds to the phase settings where the beam is not accelerated. It is determined empirically in two steps. First, the point where the energy swing changes sign is found by keeping the debunching cavity constant and varying the ramping cavity phases, see Fig. 2. And then the phase between the ramping and debunching cavity is optimised by minimizing the width and the absolute value of the skewness of the distribution Fig 3. This is done by changing the debunching phases and keeping the ramping cavity at the zero-crossing settings.

For the nominal injection process, the ramped pulse finally is the convolution of the distributions at different mean energies. An illustration is shown in Fig. 4. Thus if mean

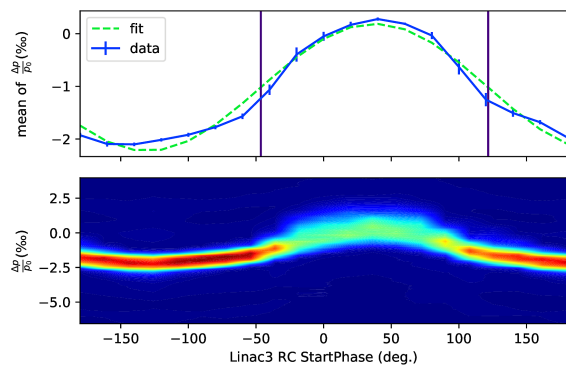


Figure 2: The determination of the zero-crossing of the ramping cavity. The mean energy of the distribution evaluated from the Schottky spectrum shortly after injection at a constant debunching cavity phase ( $70^\circ$ ) is shown as a function of the ramping cavity start phase in blue. The function follows a sinusoidal shape (green fit). The lower plot shows the contour plot of the Schottky spectrum ( $p_0$  is the reference momentum of LEIR). The purple lines in the upper plot indicate the ramping cavity phases where the beam is not accelerated. The settings are  $-48/124^\circ$ .

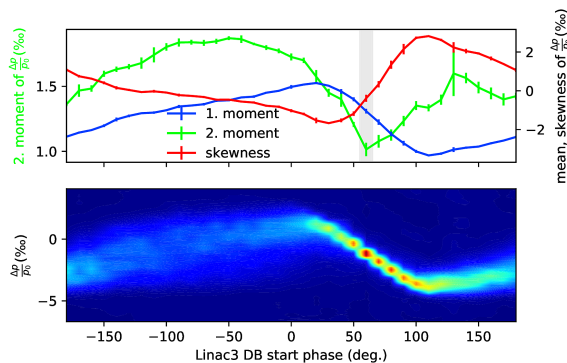


Figure 3: The zero-crossing measurement at a constant ramping cavity phase of  $-48/124^\circ$ . The debunching cavity phase is varied. The minimum of the second moment of the Schottky energy distribution (green curve) is found around  $50^\circ$  (gray shaded). The skewness vanishes at  $65^\circ$  corresponding to  $65^\circ$  phase difference between the cavities. With these settings the phase shift between the ramping and debunching cavity is compensated. ( $p_0$  is the reference momentum of LEIR).

energy and width of the constant energy ramp distributions at start and end settings of the nominal ramp are acceptable, the quality of the ramped pulse finally will also be sufficient. Figure 5 shows the evolution of the energy distribution parameters during the energy ramp, the gray shaded area indicates the extent of the operational energy swing. To monitor the evolution of the LINAC3 energy and distribution over time, the constant ramp settings that should result in no acceleration in the ramping cavity are applied to obtain a distribution as shown in Fig. 4 with the green

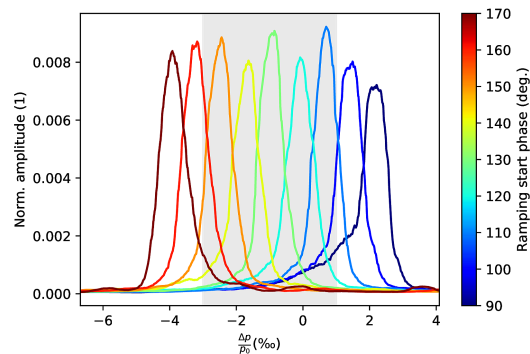


Figure 4: Measurement of momentum distribution at constant energy ramp per pulse but different energies pulse to pulse (phase difference of  $65^\circ$  between ramping and debunching cavity). The center (green) distribution has minimal second and third moment (see also Fig. 5) and is taken as a reference. An average of five measurements was taken per setting and the frequency distribution was smoothed using a rolling average. The shaded area highlights the operational energy ramping range.  $\Delta p/p_0$  is given respect of the reference momentum of LEIR.

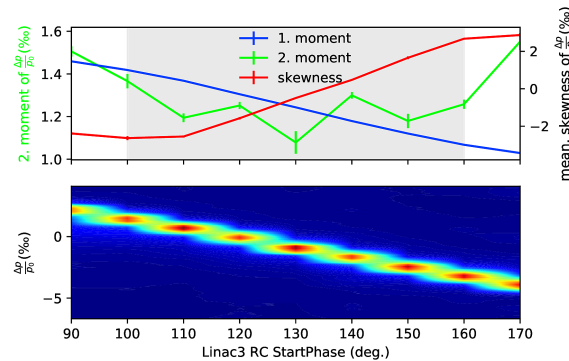


Figure 5: Evolution of the energy distribution during energy ramp. The mean moves over a span of  $-3$  to  $1\%$  around the center of the distribution w.r.t. the LEIR reference momentum  $p_0$ . The gray shaded area highlights the operational energy ramping range. The second moment (green) increases towards the edges of the operational range.

curve. Observations in the past years indicate that variations of the LINAC3 energy were mainly caused by differences with different stripping foils and their degradation with time.

## OPERATIONAL CORRECTION

### The Application

During the ion run 2018, an application to take constant energy distribution references at zero-crossing was developed. These references can be compared to online measurements from the new Schottky electronics. Energy drifts were routinely identified and corrected by this tool. Examples of a reference distribution, a distribution with energy drift as

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2019). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

well as its corrected version are shown in Fig. 6. This change in energy had occurred over a weekend and could be corrected by adjusting the tank 3 amplitude at the end of LINAC3 by 60 mV. The dependence of the tank 3 amplitude on the energy distribution at LEIR injection was measured in this context and revealed a weak correlation with mean and width of the distribution ( $-0.003\%$ /mV).

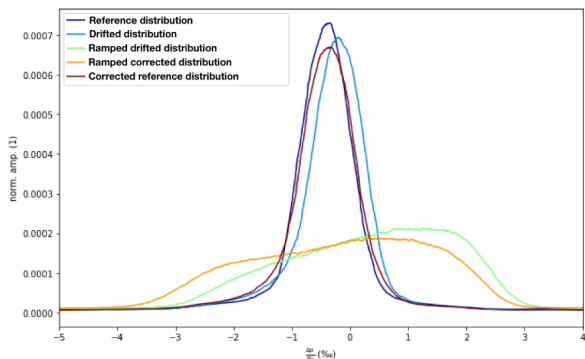


Figure 6: Comparison of reference energy distribution for constant energy ramping with online measurement before and after correction. Each curve is the average of 10 measurements. The operational distributions with ramping before and after correction are also shown. The nominal type cycle intensity increased by more than 100% from  $4 \times 10^{10}$  to  $8.42 \times 10^{10}$  charges after energy correction.

### Evolution of Energy Distribution

During the 2018 ion run the monitoring of the energy distribution from LINAC3 as described earlier was carried out over longer periods for the first time, clearly showing long term drifts with time constants of days to weeks, see Fig. 7. The observables were the mean and the second moment of the zero-crossing ramp setting energy distribution without cooling obtained parasitically on a measurement cycle. For the example in Fig. 7, the mean energy changed with a slope of  $0.06\%$  per day, which pointed to a degradation of the stripper foil. When the loss of performance was too significant, the foil was exchanged. An example of the significant change in energy distribution after a foil exchange is shown in Fig. 8. After an initial “warm-up” phase (gray area), the parameters of the energy distribution become stable and tank 3 and ramping-debunching cavities could be adjusted to the obtain the reference energy distribution parameters. Improvements are foreseen for the next ion run to ensure continuous online monitoring. Currently, the dedicated measurement cycles can be easily removed by shift crews and monitoring is stopped.

### CONCLUSIONS

In this paper, a robust way of characterising the longitudinal beam quality delivered by LINAC3 to LEIR using the Schottky monitor was presented. Reference energy distributions are obtained on dedicated measurement cycles with a special LINAC3 and electron cooling configuration.

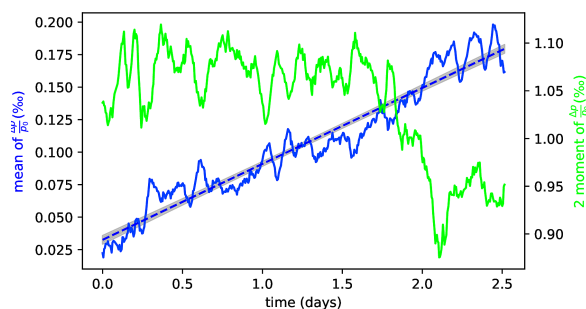


Figure 7: The change of the mean energy and width of the energy distribution over a time span of 2.5 days. A linear trend can be seen following a slope of  $0.06\%$  per day (error  $1.5\%$ ).

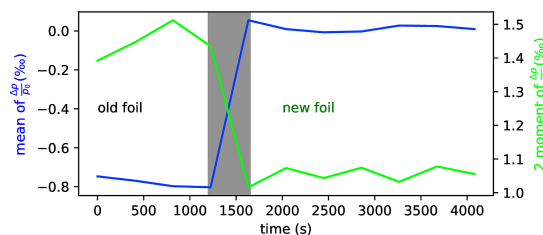


Figure 8: The change of the mean energy and width of the energy distribution after a foil was changed during the period indicated by the gray area.

They are then compared to online Schottky measurements to identify energy changes and to correct them. The LEIR performance critically depends on the injected energy distribution. Continuous online monitoring of key parameters of the energy distribution allowed to diagnose stripper foil degradation and failure. As the measurements cannot be obtained on the operational cycles, further improvements of the tools and infrastructure will be put in place for the next ion run to come. This should guarantee that the injected energy distribution is indeed always measured.

### ACKNOWLEDGEMENTS

We want to thank the hardware team for the installation and set up of the new Schottky system, which is now part of the standard acquisition system simplifying the measurements considerably. Many thanks to Ole Marqvorsen, Guillaume Baud and Diogo Alves for their efforts and fruitful interaction during the setup and installation of the system.

### REFERENCES

- [1] S. Hirlaender *et al.*, “LEIR Injection Efficiency Studies as a Function of the Beam Energy Distribution from Linac3”, in *Proc. 9th Int. Particle Accelerator Conf. (IPAC’18)*, Vancouver, Canada, Apr.-May 2018, pp. 758–760. doi:10.18429/JACoW-IPAC2018-TUPAF034
- [2] S. Hirlaender *et al.*, “Studies of the Injection and Cooling Efficiency in LEIR Using the Longitudinal Schottky Spectrum”,

in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 765–767. doi:10.18429/JACoW-IPAC2018-TUPAF036