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STUDIES OF THE INJECTION AND COOLING EFFICIENCY IN LEIR USING THE LONGITUDINAL SCHOTTKY SPECTRUM

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Abstract

The CERN Low Energy Ion Ring (LEIR) has two main operational beams with their associated cycles, the so-called EARLY and the NOMINAL beam. The EARLY beam consists of a single injected pulse from the LINAC3 accelerator, whereas seven consecutive injections are accumulated, and electron cooled for the NOMINAL beam. In both cases, the longitudinal Schottky monitor allows assessing the longitudinal particle distribution during the cooling process on the injection plateau. A method has been established to analyze the Schottky signal, reconstruct the initial particle momentum distribution and derive relevant parameters such as the cooling time, energy off-set of injected and stacked beam or the momentum distribution of the lost beam. The variations of the obtained parameters and the impact on the LEIR performance will be addressed.

INTRODUCTION

The CERN LEIR machine receives ion beams at 4.2 MeV/u from the LINAC3 accelerator and accelerates this beam to 72 MeV/u - the injection energy of the CERN PS, the next machine in LHC ion chain. The LINAC3 pulses are 200 μs long. Seven of these pulses are injected into the LEIR in case of the NOMINAL beam and only one for the EARLY beam. Each linac pulse is injected over 70 turns filling the LEIR 6D phase space [1]. In case of the EARLY cycle, the beam is cooled after injection by the LEIR electron cooler for about 400 ms without changing the mean energy of the injected stack. For the NOMINAL cycle, the electron cooler does not only reduce the phase-space volume of the beam but also changes the mean energy (dragging) of the beam to make space for the next injection that will arrive 200 ms later. Non-optimized cooling and dragging for a given injected particle distribution results in particle losses. The LEIR longitudinal Schottky pick-ups are used to characterize the injected momentum distribution as well as various cooler parameters. A method to re-construct the initial distribution from the Schottky signals will be introduced in this paper. The method will then be used to measure cooling time and other parameters associated with injection efficiency.

THE LONGITUDINAL SCHOTTKY SPECTRUM OF A COASTING BEAM

The Momentum Distribution Reconstruction

A detailed introduction can be found in [2], [3] and [4]. The Schottky signal is obtained from a pick-up, measuring current. In a theoretical approximation, a charged particle with a specific revolution time t_p and a time shift t_s produces a current I at the measurement position in the ring:

$$I(t) = \frac{eZ}{t_p} \sum_{m\in\mathbb{Z}} \delta(t - t_s - mt_p), \tag{1}$$

Due to its periodicity with the period $\omega_0 = \frac{2\pi}{t_p}$ it can be expressed as:

$$I(t) = eZ \sum_{m\in\mathbb{Z}} e^{im\omega_0(t-t_s)}. \tag{2}$$

In Fourier space the transformed function becomes:

$$I(\omega) = eZ\omega_0 \sum_{m\in\mathbb{Z}} \delta(\omega - m\omega_0)e^{im\omega_0 t_s}. \tag{3}$$

For a large number of particles N with random initial time shifts and calculating the squared absolute value of I yields:

$$|I(\omega)|^2 = (eZ\omega_0)^2 \sum_{s,s'=1}^{N} \sum_{m\in\mathbb{Z}} \delta(\omega - m\omega_0)e^{im\omega_0(t_s - t_{s'})} \tag{4}$$

Since the phases are equally random distributed, summing up yields:

$$|I(\omega)|^2 = N(eZ\omega_0)^2 \sum_{m\in\mathbb{Z}} \delta(\omega - m\omega_0) \tag{5}$$

This is the Fourier signal of a mono-energetic beam, consisting of N particles. Let's assume now a total number of particles N_{tot} with a frequency distribution $P_\omega(\omega_0)$ such that $N_{tot} = \int P_\omega(\omega_0)d(\omega_0)$:

$$\begin{aligned} |I(\omega)|^2 &= (eZ)^2 \sum_{m\in\mathbb{Z}} \int d\omega_0 P_\omega(\omega_0){\omega_0}^2\delta(\omega - m\omega_0) \\ &= (eZ)^2 \sum_{m\in\mathbb{Z}} P_\omega(\tfrac{\omega}{m})\frac{\omega^2}{m^3} \end{aligned} \tag{6}$$

With equation (6) the revolution frequency or momentum distribution can be calculated from the Schottky current distribution. Selecting a specific frequency band m equation (6) simplifies to:

$$P_\omega(\omega) \propto m\left(\frac{|I_m(m\omega)|}{\omega}\right)^2. \tag{7}$$

Figure 1 illustrates the result in equation (6). At each harmonic m of ω_0 the initial frequency distribution is transformed into the so-called Schottky band. For low harmonics the frequency resolution may be too small, and at higher harmonics the bands may overlap. It is possible to calibrate

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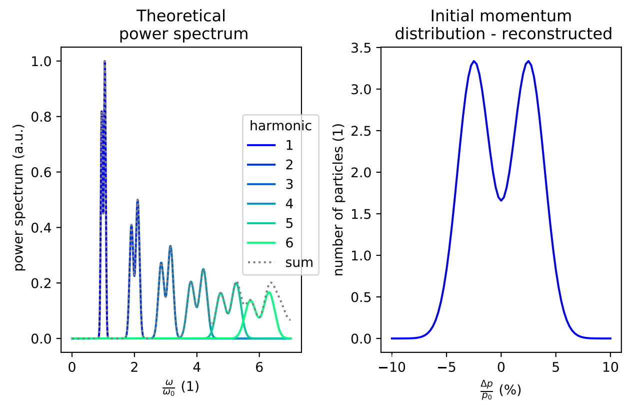

Figure 1: The reconstruction of the initial momentum distribution (shown right) from the (theoretical) power spectrum (shown left). The quantitative behavior of the spectrum is given in Eq. (7). Note the overlap at higher harmonics which is a complication for the reconstruction. In the measurement only the sum of all bands (dashed gray line) is available.

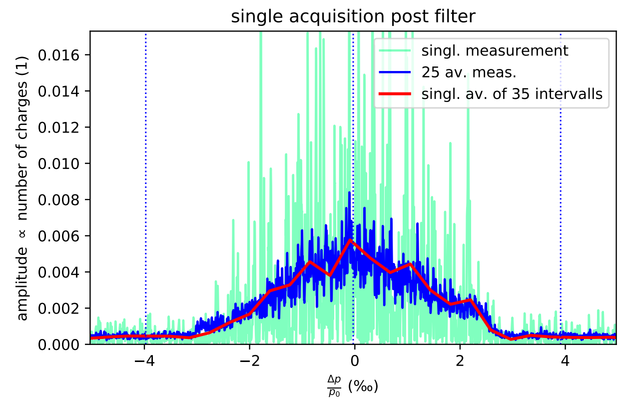

Figure 2: Reconstruction of the initial momentum distribution of a single acquisition by post filtering the spectrum in comparison to the signal obtained from 25 independently taken and averaged acquisitions. The measurements were taken at the 50th harmonic of ω_0.

P with an independed intensity monitor (e.g., a BCT), and consequently the Schottky can also be used for measuring intensity at injection. With the relation $\frac{\Delta\omega}{\omega_0} = \eta\frac{\Delta p}{p_0}$, where η is the slip factor, the distribution P of Δp can be given:

$$P(\Delta p) := P_\omega(\omega(\Delta p)) = P_\omega(\omega_0(1 - \eta\frac{\Delta p}{p_0})). \tag{8}$$

APPLICATIONS IN LEIR

The Operational Measurement

The Schottky measurement is inherently noisy, and the parametrization can be very demanding. One possibility to obtain results with a high time resolution of the evolution of the spectrum during the injection plateau is averaging over several independently measured spectra. Another very successful approach in LEIR was to divide the frequency span into equal intervals and to take their average value of a single measurement. An example of the spectra obtained with and without averaging is given in Fig. 2 for a division into 35 intervals.

The EARLY Cycle

As discussed earlier, the cooling performance is crucial for the LEIR performance. The EARLY cycle is 2.4 s long. It was the main cycle used for the Xe run in 2017. Applying the previously mentioned filter technique for the longitudinal Schottky spectra, it was possible to follow the evolution of the momentum distribution along the injection plateau. The red line in the upper plot of Fig. 3 corresponds to the median of the momentum distribution. The width of the distribution is defined as the part of the spectrum around the median containing 66% of the intensity. The evolution of the width is shown in the lower plot of Fig. 3. An exponential fit of

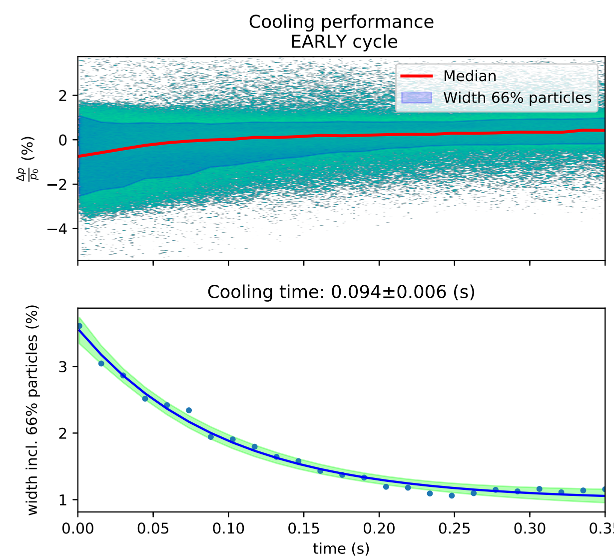

Figure 3: The cooling performance is characterized by the cooling time. The evolution of the width of the distribution around the median containing 66% of the particles is fitted with an exponential function to estimate the cooling time.

the width over time allows to estimate the cooling time. It amounts to 0.094 s in this particular example.

The NOMINAL Cycle

The Nominal cycle is 3.6 s long which allows accumulating higher intensity due to multiple injections on the longer flat bottom. Optimizing the cooling, dragging and multi-turn injection parameters to free sufficient phase-space volume for subsequent injections is not straight forward. Figure 4 shows the evolution of the Schottky spectrum for several injections in LEIR. Particles that are at the location of the next injected beam in momentum space at the moment of in-

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jection will be lost. The stacked beam shows a typical space charge driven double peak structure (details see e.g. [5]).

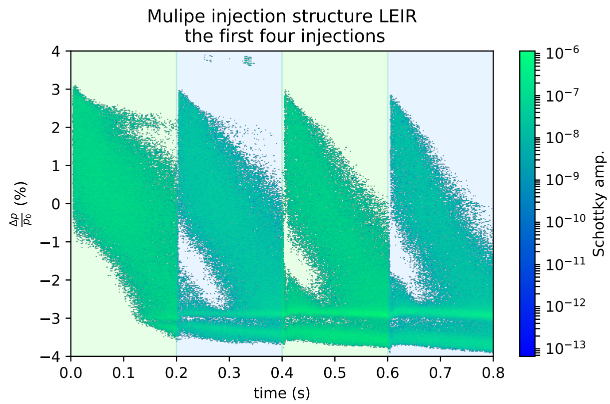

Figure 4: Schottky spectrum for several injections into LEIR. Several 200 μs pulses arrive from Linac3, are injected and dragged to lower momentum to provide space for the next injection where the beam is further cooled. Particles that remain in the area where new beam will be injected are lost. The shaded background shows the 200 ms cooling time of each of the consecutive injections.

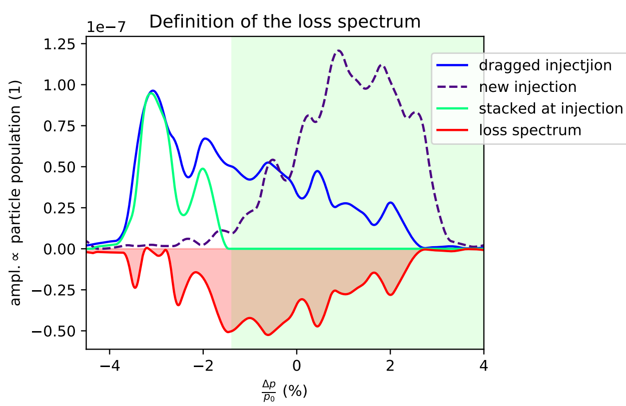

Figure 5: The loss spectrum (red area) is the lost beam due to the injection process and insufficient dragging and cooling of the previously injected beam. The blue line depicts the distribution shortly before the new beam is injected. The dashed line shows the distribution of the incoming beam. After injection, the green line illustrates the remaining stacked beam, while particles within the green shaded area were lost.

To calculate the amount of lost beam from the Schottky spectrum, the spectrum is recorded before and shortly after the new beam is injected, as shown in Fig. 5. After removing the part of the newly injected beam from the dragged distribution, the spectrum of the lost beam is obtained. Because the area of the distribution is proportional to the number of particles, the signal could be calibrated to the LEIR beam current transformer (BCT). The loss results from the Schottky are then compared to data obtained directly by the BCT.

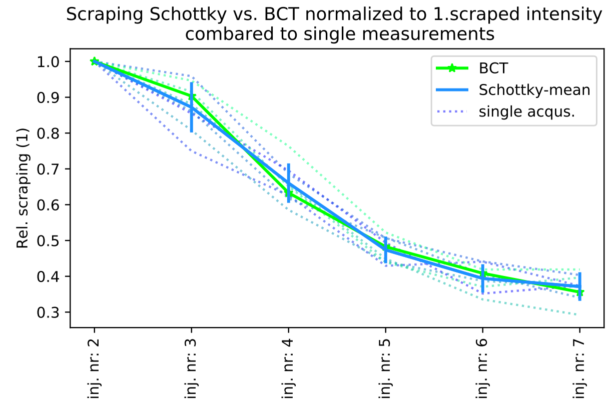

Figure 6: The comparison of the intensity which is lost during the injection process measured by the BCT and the calibrated Schottky system, normalized to the first injection. Good agreement has been obtained with the Schottky and BCT data.

The comparison is shown in Fig. 6. The Schottky data is in good agreement with data from the LEIR BCT.

CONCLUSIONS AND OUTLOOK

The reconstruction of the initial momentum distribution from the longitudinal Schottky signal as well as its evolution allowed understanding some of the origins of reduced injection efficiency for LEIR multi-injection cycles. The cooling performance as well as characterization of beam loss at the moment of the next injection were addressed. The presented methods will be used in the future to directly calculate cooling or other correction settings to easily control the injection process and guarantee optimum injection efficiency.

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