BEAM DIAGNOSTICS WITH SCHOTTKY NOISE IN LEIR

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Abstract

The high density Lead ion beams, needed for LHC, are obtained in the Low Energy Ion Ring (LEIR) at CERN by multi-turn injection followed by electron cooling and stacking. During this injection and stacking phases where the circulating beam is unbunched, diagnostics with Schottky noise are used for probing essential beam parameters, such as tune, momentum spread, emittance and their evolution with time… The hardware facility and first results obtained during the recent commissioning of LEIR are described.

INTRODUCTION

The CERN LEIR machine is an essential part of the LHC injection chain for supplying high brightness ion beams [1]. Basically it transforms a series of low intensity and long Linac pulses into dense and short bunches by stacking and phase-space cooling. The accumulation principles involving multi-turn injection [2] and electron-cooling have been successfully tested in the past [3]. Each Pb^{54+} pulse is injected during 70 turns then cooled for 400ms. A total of four Linac pulses are required for accumulating 9.10^8 un-bunched ions. The bunches are accelerated from 4.2MeV/u up to 72MeV/u, then ejected towards the downstream machines. Widely used in circular machines Schottky pick-ups extract beam parameters from the analysis of the random component of the coasting beam current. The basic concepts of Schottky theory are given before describing the devices installed and the first measurements.

SCHOTTKY NOISE BASICS

Longitudinal Signal

A detailed derivation of the Schottky theory is not within the scope of this paper. Basic information on this topic can be found in the following short list of papers [4, 5, 6, 7]. In a storage ring, a single particle of charge Ze circulating at a revolution frequency $f_k = 1/T$ induces a series of δ functions onto a short pick-up placed somewhere around the ring. With a passage time t_k given by initial conditions, the current created and its Fourier expansion are:

$$\begin{aligned} i_k(t) &= Zef_k \sum_m \delta(t - t_k - mT) \\ &= Zef_k \left(1 + 2\sum_{n=1}^{\infty} \cos n\omega_k (t - t_k) \right) \end{aligned} \quad (1)$$

The so-called longitudinal spectrum consists of a DC part $i_{k0} = Zef_k$ which is the circulating beam current, and an infinite series of lines at all harmonics of f_k. Now assume an un-bunched beam of N individual particles with random initial phases φ_k and revolution frequency f_k within a distribution $f_0 \pm \Delta f/2$. Averaging $i_k(t)$ over N particles gives the circulating beam current $I_0 = N(Zef_0) = N \cdot i_0$. Further, each particle contributes to its own series of harmonic lines. The latter are indistinguishable for an observer who instead will see at the harmonic $n \cdot f_0$ a Schottky band of width $n \cdot \Delta f$, as the mean square current fluctuations is not zero. The spectral line at $n \cdot f_0$ can be written as :

$$< I_n^2 >= (2i_0)^2 \left(\frac{1}{2} \left[\sum_{k=1}^{N} \cos n\varphi_k \right]^2 + \frac{1}{2} \left[\sum_{k=1}^{N} \sin n\varphi_k \right]^2 \right) \quad (2)$$

The initial phases being randomly distributed, the sums over cross-terms cancel and

$$< I_n^2 >= (2i_0)^2 \left(\frac{1}{2} \sum_{k=1}^{N} \cos^2 n\varphi_k + \sin^2 n\varphi_k \right) = 2(Ze)^2 f_0^2 N \quad (3)$$

From Eq.(3), it turns out that the total noise power per band (dissipated in a 1Ω resistor) is constant and not harmonic dependent. However the power spectral density scales as $1/n\Delta f$. Thus longitudinal Schottky spectra give the mean revolution frequency and the momentum spread

$$n \times \Delta f = nf_0 \eta (\Delta p / p) \quad (4)$$

where $\eta = \left| 1/\gamma^2 - 1/\gamma_{tr}^2 \right|$ is the off momentum parameter of the machine. With a calibrated system, the number of particles can also be deduced [8].

Transverse Signal

The betatron motion of amplitude a_k, of a single particle at a fixed observation point is described as

$$x_k(t) = a_k \cos(\omega Q t + \phi_k) \quad (5)$$

A position pick-up is sensitive to the dipole moment $d_k(t)$ which can be interpreted as the amplitude modulation of the longitudinal current :

$$d_k(t) = x_k(t) \cdot i_k(t) = a_k \cdot i_0 \cdot \sum_n^{\infty} \cos((n \pm q)\omega t + n\varphi_k \pm \phi_k) \quad (6)$$

where q is the fractional part of the tune Q. The spectrum at a given harmonic n of the revolution frequency features two sidebands at $(n \pm q)f$. As for the longitudinal case, the total noise power per transverse band is not harmonic dependent. The average power in each sideband is the same for uncorrelated particles with ramdom phase :

$$< D_{n\pm q}^2 >= \frac{a_{rms}^2}{2} (Ze)^2 f_0^2 N \quad (7)$$

where a_{rms}^2 is the r.m.s beam size, proportional to the transverse emittance. The widths of the sidebands at $(n \pm q)f_0$ are obtained by substituting q by $(q+\Delta q)$ and f_0 by $(f_0+\Delta f)$:

$$\Delta f_{n\pm q} = (n \pm q)\Delta f \pm f_0 \Delta q \quad (8)$$

Hence transverse Schottky spectra provide a large set of fundamental beam parameters: the fractional part of the tune, the tune and momentum spreads, the chromaticity, the transverse emittance and the mean revolution frequency.

SCHOTTKY PICK-UPS

Two existing systems, inherited from the former Low Energy Antiproton Ring (LEAR) at CERN have been brought back to operation. Both consist of a succession of short strip-line pick-ups. However they differ by the way the signals from the individual strip-lines are combined :

The "Travelling wave" system is suitable only for low energy particles at injection ($\beta = 0.0947$). The striplines are connected in series, with appropriate electrical delays so that the currents from all electrodes are added. The signal is extracted at the downstream electrode, amplified and processed. There is one pick-up per transverse plane. The horizontal one yields also longitudinal information.

In the second configuration, the backward signal from each individual strip-line is directly amplified, delayed then summed using power combiners. Although this scheme yields a poorer signal to noise ratio than the travelling wave system, it can be applied for any particle velocity. One pick-up is used for measuring signals in both longitudinal and horizontal planes, and a second one serves for the vertical plane.

The longitudinal/horizontal pick-up consists of 24 pairs of striplines in series and 64dB amplification is enough for beam observations. The vertical pick-up having 6 pairs, needs an amplification gain of 92dB. The signals are split either towards a spectrum analyser, or an FFT-based spectral analysis system.

Each stripline electrode can be considered as a matched transmission line connected to the amplifier input having 50Ω input/output impedance (Figure 1a). A real amplifier can be modelled as an ideal (noiseless) amplifier with an external equivalent noise source connected at the amplifier input. In that case, the equivalent input noise power density is

$$\frac{I_v^2}{\Delta f} = \frac{kT}{R} 10^{\frac{NF}{10}} \tag{9}$$

where k is the Bolztmann constant, T the load temperature, R the pick-up load impedance, NF, the so-called noise figure which reflects the intrinsic amplifier noise, is expressed in dB here.

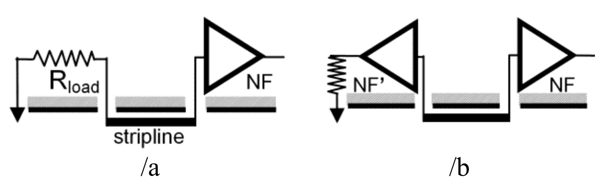

Figure 1: a/Basic stripline electrode configuration. b/ A low noise amplifier replaces the load resistor for noise reduction purposes.

Evaluation of the difference of noise power density between a real amplifier characterized by NF' and an ideal one shows that the intrinsic amplifier noise is equivalent to an internal noise source (a 50Ω resistor here) whose effective input noise temperature [9] is

$$T' = T(10^{\frac{NF'}{10}} - 1) \tag{10}$$

Putting numbers in [eq.10] with *T=293K* and *NF'=1.2dB* gives *T'=93K*. Replacing the standard matching load at room temperature by the input impedance of a very low noise amplifier, as depicted in Figure 1b turns *T* into *T'* in [eq.9]. The left amplifier then acts as a pseudo cold load. For *NF'=NF* the equivalent input noise in the case of Figure 1b is 5.8 pA/Hz$^{1/2}$ which means a noise reduction of 5dB as compared to the configuration of Figure 1a.

RESULTS

In October 2005, the first commissioning phase of the LEIR ring has been carried out with O^{4+} ions instead of Pb^{54+}[10]. The power spectral density is proportional to $(Ze)^2 N_{ion}$: consequently for a constant number of charges, the signal to noise ratio is significantly lower with light ions than with heavy ions. This limiting factor could be overcome with active loads (Table 1)

Table 1: Signal to noise ratio obtained with O^{4+} .

plane	Longitudinal	Horizontal	Vertical
S/N with O^{4+}	10	4.5	2.3

Since the machine start-up this year, the injection scheme with Pb^{54+} ions has been successfully tested. The longitudinal spectrum shown in Figure 2 has been recorded during the injection phase, at the 100th harmonic of the revolution frequency f_0*=358 kHz*. The LEIR cycle was programmed to take two Linac pulses : A/ a first pulse is injected, and placed onto a stacking orbit after being cooled. Hence the spectrum width shrinks proportionally to the momentum spread reduction; B/ a second warm pulse follows 400ms after the first one - note that cooling has already taken place here; C/ at the end of the two injection-cooling steps, the cold beam is brought back to the nominal orbit for adiabatic bunching. From the FWHM measurements of the spectrum lines, one could deduce a drop of the momentum spread from 4.08×10^{-3} down to the nominal value of 2.13×10^{-4}. Although no calibration was performed, an attempt to estimate the number of circulating ions from the area of the spectrum line gives 4×10^{8} particles. The figure is a factor 2 higher than the value obtained with the DC current transformer.

Space-charge induced modification of the longitudinal spectrum has also been observed for long cooling times. The spectral line splits into two peaks due to plasma waves running forward and backward through the circulating beam [11, 12].

Incoherent betatron tunes, tune spreads and chromaticities are obtained from transverse spectra acquisitions, equation (8) giving the sideband frequencies. Results are summarised in Table 2.

Table 2: Beam parameters during the injection phase, without compensation.

	tune	dq/Q	ξ
Horizontal	1.82	7.7×10^{-3}	-1.92
Vertical	2.72	4.4×10^{-3}	-1.10

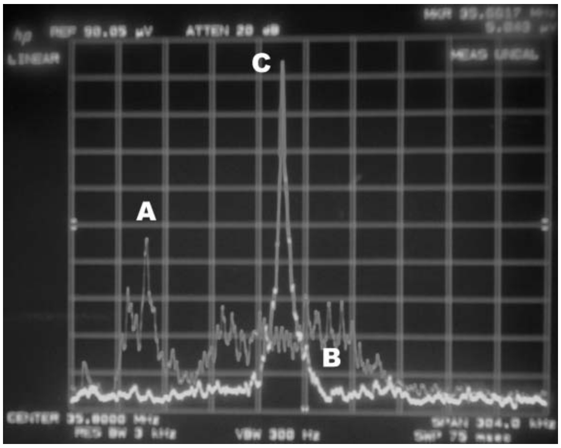

Figure 2: Evolution of the longitudinal spectrum with time. A/ the first linac pulse is injected, cooled an stacked. B/ a second pulse follows thereafter. C/ The cold coasting beam is brought to the nominal revolution frequency before bunching.

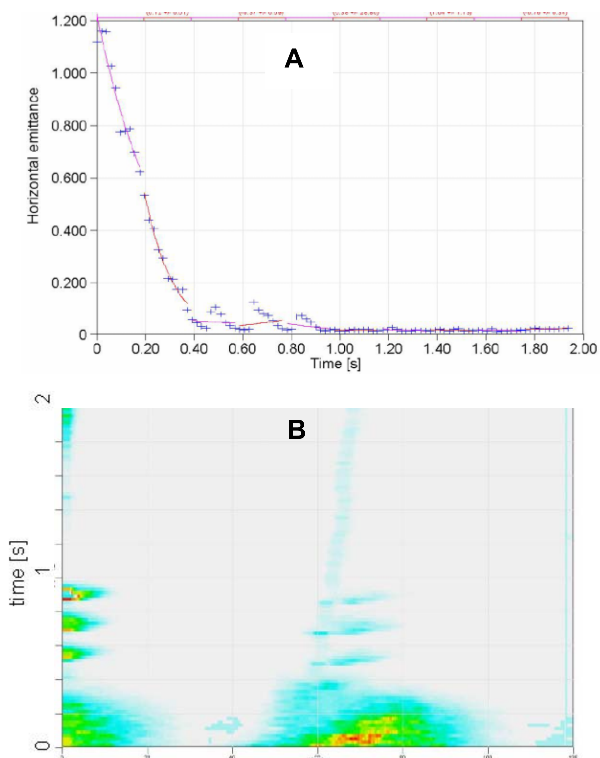

Figure 3: A: Plot of the horizontal emittance versus time. B: Its associated waterfall representation of the horizontal spectra (frequency span =102 kHz here) versus time.

The FFT-based spectral analysis system provides a set of essential information for cooling studies [13]. Figure 3A shows the evolution with time of the relative horizontal emittance during the operation of the cooler. Another typical view is is the waterfall plot of the horizontal Schottky spectra during the same measurement (Figure 3B).

CONCLUSIONS

Schottky pick-ups have been routinely used for the commissioning of LEIR with coasting beams since October 2005, showing evidence of dynamic phase space cooling. Further studies and optimizations are one the way. Combining travelling-wave structures and active loads allows a significant gain of the signal to noise ratio. The Schottky system has to be calibrated for intensity measurements. Data with high beta particles will be available during the next run in September.

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