ISBN: 978-3-95450-230-1 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2021-WEPP04



# SCHOTTKY SIGNAL FROM DISTRIBUTED ORBIT PICK-UPs

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*Abstract*

In the CERN Extra Low ENergy Anti-proton (ELENA) ring, intended for the deceleration of antiprotons, the longitudinal Schottky signal is obtained by summing the multiple electrostatic pick-up (PU) signals that are also used to measure the closed orbit. The signals from the individual PUs are phase-compensated to a single, common longitudinal location in the machine and added in the time domain. In this contribution, the related theoretical phase compensation is calculated and compared to measurements. We show how the cross correlation between the Schottky noise from the individual PUs can be used to find the correct phase-compensation for an optimal signal-to-noise ratio (SNR). This improvement in terms of SNR is, as expected, proportional to the square root of the number of PUs. The capability of the system to measure both, the bunched and the un-bunched low intensity (~$3\cdot10^7$ $H^-$ @ 100 keV / 144 kHz) beams is confirmed by the experimental results presented. Furthermore, the inter-bunch phase correlation is briefly addressed and, for the case of bunched beams, the Schottky signal levels once down converted to different harmonics of the revolution frequency ($f_{rev}$) are presented. In applications where the coherent beam signal dominates the spectrum and limits the dynamic range of the signal processing system, a down-conversation to a non-integer multiple of the RF harmonic is proposed as a way to reduce the coherent signal level.


## THE MEASUREMENT SYSTEM

The digital part of the CERN ELENA orbit measurement system is implemented on in-house designed VME Bus Switched Serial - Digital Signal Processor – Field Programmable Gate Array Mezzanine Card (VXS-DSP-FMC) carrier boards, carrying FPGAs, FMCs and DSPs with the possibility to transmit data between them via the VXS bus [1]. The key features of the VXS-DSP-FMC carrier, used in this extension of the ELENA orbit system [2], is the possibility to synchronize local oscillators across cards for all down-converters and pass real-time data between DSPs.

The orbit system already uses the sum and the delta signals from all PUs, as these analog signals are connected to inputs of the ADCs. To extract the longitudinal Schottky signal only the sum signals are used. Each PU sum signal is individually down-converted by a configurable harmonic of the revolution frequency. In ELENA, the Schottky system functionality is typically used for un-bunched beam, whereas the orbit system functionality is used for bunched beam. Using the same down-mixers, the two functions can operate on different harmonics while sharing the same hardware in a time-multiplexed fashion or operate simultaneously if using the same harmonic. The relative phase difference between the individual local oscillators (LOs) used in the down-converters must be kept minimal for a successful phase compensation, otherwise it would introduce an unwanted phase shift between the various down-converted signals. The zero phase between LOs is obtained by a simultaneous reset of the phase accumulators in the Direct Digital Synthesis (DDS) used as local oscillators.

The expected bandwidth of the longitudinal Schottky signal in ELENA dependents on the beam energy and the cooling status and is 50 Hz – 200 Hz times the chosen Schottky harmonic. The sampling time, and hereby the bin width of the resulting Fast Fourier Transformation (FFT), can be chosen from 20 ms to 650 ms per spectrum, resulting in a bin width range of 48 Hz to 1.5 Hz. Up to a total of 128 spectra can be sampled on one or two energy levels during the ELENA cycle where beam cooling is performed.

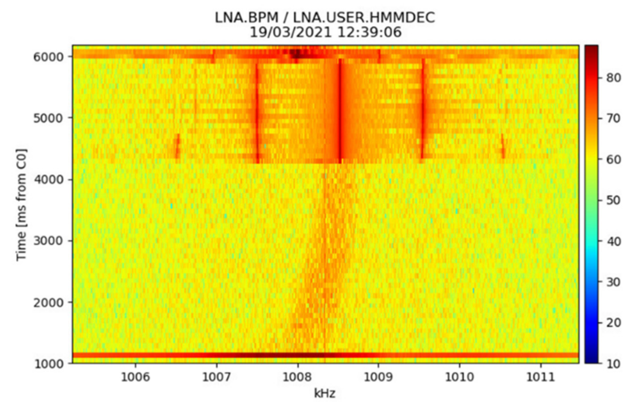


Figure 1: The measurement shows longitudinal Schottky in ELENA [3] as a function of time i.e. for both un-bunched and bunched beam.

The measurement shown in Fig. 1 is performed, on a flat 100 keV energy level in the ELENA deceleration cycle, using the phase compensating technique i.e. phase-compensating and adding 16 PUs down-converted from the 7th harmonic of the revolution frequency, with $f_{RF} = 4\ f_{rev}$ in the bunched part. The beam is injected at approximately 1080 ms relative to machine cycle start (C0), it is then debunched, slightly changed in energy using the electron cooler and re-bunched at approx. 4250 ms.

## LONGITUDINAL SCHOTTKY SIGNALS

A single particle circulating in an accelerator will, on a sum PU, generate a series of Dirac pulses spaced in time by the revolution time $\tau_{rev}$, i.e. a Dirac comb. The Fourier series of this signal is given by:

$$s(t) = \frac{1}{\tau_{rev}} \sum_{n=-\infty}^{\infty} e^{j\cdot n2\pi\frac{t}{\tau_{rev}}}. \qquad (1)$$

For beam diagnostics purposes typically, a particular harmonic is selected for the Schottky signal observation. The

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Schottky signal around any harmonic of the revolution frequency is a superposition of the Dirac pulses from all particles in the ring. If the beam is un-bunched beam, the spectrum will be continuous around each harmonic of the revolution frequency. If the beam is bunched, i.e., RF voltage is applied to the de-accelerating cavities, the revolution frequency of the individual particles will continuously be changed around a nominal value of the synchronous particle. This results in a frequency modulation and the signal spectra peaks at every harmonic of the revolution frequency, surrounded by synchrotron sidebands [4].

## THE PHASE COMPENSATION

To constructively add the signals from different PUs distributed around an accelerator ring, their theoretical phase difference can be calculated either from the known physical location of each PU, or by performing a cross correlation between the down-converted PU sum signals from a reference PU and the PU to be phase compensated.

### Physical Pickup Location

The phase difference, not including cable lengths ($\Delta\varphi_{nc}$), between two PU sum signals of a particular revolution frequency harmonic is given by the observation frequency ($f_{Schottky}$) and the time of flight (Δt) of the particle between the two PU locations. $\beta c$ being the speed of the particles. $l_{ELENA}$ the circumference of the accelerator and $l_{\Delta\_PUs}$ the distance between the two PU.

$$\Delta\varphi_{nc} = 2\pi f_{Schottky}\Delta t = 2\pi \cdot h_{Schottky} \cdot f_{rev} \cdot \Delta t,$$

where

$$f_{rev} = \frac{\beta c}{l_{ELENA}} \; and \; \Delta t = \frac{l_{\Delta\_PUs}}{\beta c}.$$

It follows, that

$$\Delta\varphi_{nc} = 2\pi h_{Schottky} \frac{l_{\Delta\_PUs}}{l_{ELENA}}. \qquad (2)$$

As Eq. (2) shows, $\Delta\varphi_{nc}$ only depends on the physical distance between the PUs and the chosen observation harmonic ($h_{Schottky}$) of $f_{rev}, i.e.$ all the frequencies in the spectra at that harmonic can be compensated by the same $\Delta\varphi_{nc}$ correction. By applying a phase delay in the complex plane to the sampled quadrature (IQ) data from a particular pickup location ($IQ_{PUposition2}$), using the calculated $\Delta\varphi_{nc}$ correction, we can transform the IQ data to the location of another (reference) PU:

$$IQ_{PUposition1} = IQ_{PUposition2} \cdot e^{-j\Delta\varphi} \qquad (3)$$

One particular PU is chosen as reference location and all other PU signals are phase shifted to this reference location, before all the PU signals are added, followed by a Fast Fourier Transformation (FFT) to evaluate the longitudinal Schottky spectra. In the CERN ELENA system this phase compensation is performed on the down-converted, decimated data.

Equation (2) assumes an equal length of the signal cable between each PU and the signal acquisition system. In the case of different cable lengths an additional cable phase compensation term is required to find the needed phase $\Delta\varphi_{cld}$:

$$\Delta\varphi_{cld} = \Delta\varphi_{nc} - 2\pi h_{Schottky} \cdot f_{particle} \cdot \frac{l_{cld}}{c \cdot \beta_{cable}} \qquad (4)$$

with $l_{cld}$ being the cable length difference between the two PUs of interest to the acquisition system, $c \cdot \beta_{cable}$ the signal speed on the cable and $f_{particle}$ the revolution frequency of an individual particle. Now the $\Delta\varphi_{cld}$ correction depends on the revolution frequency of each individual particle, i.e. phase compensation is different over the measurement frequency band. However, in case of ELENA the bandwidth of the Schottky signals at, e.g. the 14$^{th}$ harmonic of $f_{rev}$ is expected to be approximate 700Hz. The difference in $\Delta\varphi$ calculated at the 14$^{th}$ harmonic of $f_{rev}$, for a cable length difference of 10m and $f_{rev}$ – 350 Hz vs. $f_{rev}$ + 350 Hz is negligible. Equation (4) can therefore be used with $f_{particle} = f_{rev}$ giving the needed phase, $\Delta\varphi_{cld}$ for correction including the phase change caused by cable length differences, but not including phase difference across the bandwidth of the Schottky signal.

### Cross-correlation

Performing a cross-correlation on sampled IQ data from two different PUs will also reveal the Δφ required for the phase compensation for an optimum constructive summing of these two PU signals. A high SNR is needed as the input to the cross-correlation to get a precise phase i.e., the $\Delta\varphi$ is best found from bunched beam signals, but can following be used also on un-bunched beam data. Any spurious signals in the data will disturb the result of the cross-correlation.

The $\Delta\varphi$ calculated from the physical location Eq. (4) of the PUs is used in the ELENA Schottky system, while the cross-correlation method is used as validation of the optimum $\Delta\varphi$ correction value.

### Phase Sweep

As a sanity check we applied a $\Delta\varphi$ sweep 0° – 360° on the IQ data, from a bunched beam signal, from one particular PU and added this term following Eq. (3) to the IQ data from another PU (simultaneously sampled and down mixed with both local oscillators in phase and on the same harmonic of $f_{rev}$), followed by an FFT. The spectrum shows the expected bunched beam Schottky signal pattern, similar as shown in the upper part of Fig. 1 (where the beam is bunched after 4250ms). In Fig. 2 we plot the amplitude of the central harmonic line, the first lower and the first upper satellites of the Schottky spectrum. For this data the constructive / destructive interference is clearly observed at $\Delta\varphi = 40°$ and 220° respectively. The peak and dip of the signal amplitudes coincide at the same phase for all three traces, and the sum at the destructive phase approaches the noise floor, indicating a high correlation between the two signals.

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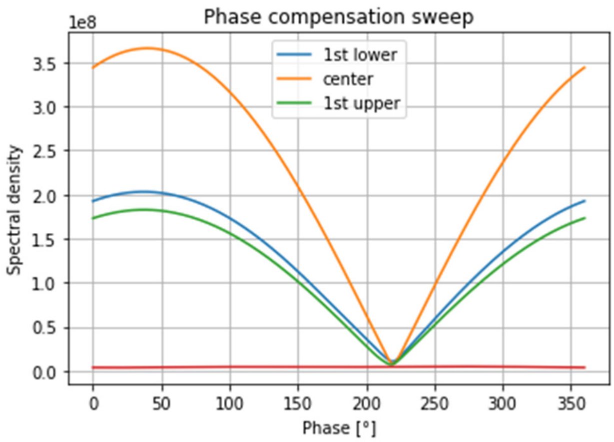


Figure 2: The amplitude of the three main spectral peaks in the bunched beam spectrum found from adding two PUs (one PU being phase shifted), as a function of the phase compensation.

The constructive peak phase agrees with the $\Delta\varphi$ found by both methods, the cross-correlation on IQ data between the two PUs and from the physical location including the cable length compensation (Eq. (4)).

## SNR IMPROVEMENT

Acquiring and analysing low-level Schottky signals near the equivalent thermal noise level, averaging of the spectra data is a common method to improve the SNR. If the averaged Schottky signal data is correlated and the thermal related noise signal contribution is uncorrelated, the theoretical SNR improvement is 3dB for each doubling of the number of signal sources.

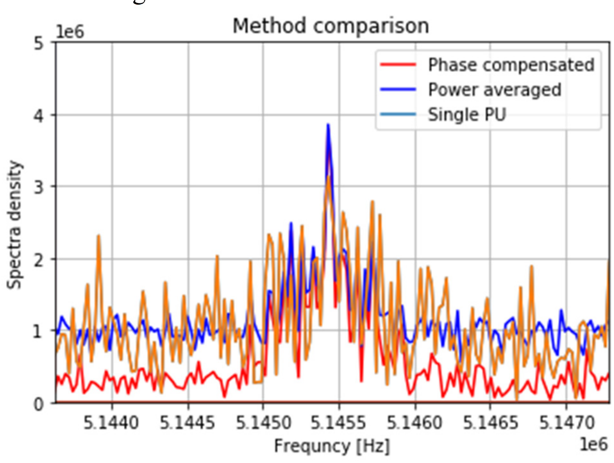


Figure 3: Comparison of noise reduction methods: Single PU vs. power average of spectra vs. presented phase compensated method. The beam is un-bunched and observed at 14$^{th}$ harmonic of $f_{rev}$.

In Fig. 3 the longitudinal Schottky spectrum from a single PU is compared with the spectrum generated by the same beam, but taking the average of 13 consecutive spectra. The noise amplitude decreases for the averaged spectra compared to single PU spectrum. Furthermore, under the same beam condition, the combined spectra of 13 phase-compensated PUs is shown, with the signals normalized to the number of PUs. The latter shows the substantial improvement on the SNR, compared to simple averaging of a single PU data, which is basically limited to average out the noise contribution, whereas the presented phase compensating method on top lowers the background noise, thus improves the SNR. The SNR improvement has been evaluated for 2, 4, 8 and 13 PUs. The results are shown in Fig. 4 and they follow well the expected $\sqrt{number\ of\ PUs}$ dependency. The result clearly indicates the benefit of a constructive signal summing, when using phase-compensated signals from BPMs in different locations of an accelerator.

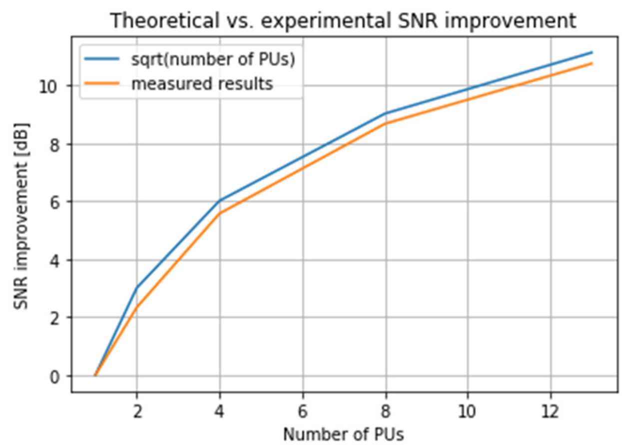


Figure 4: Theoretical and experimental SNR improvements vs. number of PUs used.

## INTER BUNCH PHASE CORRELATION

The $\Delta\varphi$ correction calculated from the physical PU location should not be confused with the longitudinal phase relationship between particles in bunched beams: With a single particle in a ring and two PUs 180° in circumference apart, given by their relative physical location, the two sum signals added would cancel for the 1$^{st}$ harmonic of $f_{rev}$ (unless phase compensated), whereas for the 2$^{nd}$ harmonic of $f_{rev}$ the summing will be constructive. The same holds for any number of particles in the ring, as the Schottky signal is a superposition of signals generated by all individual particles. Limiting our considerations only to the central revolution harmonic: With two particles in a ring 180° apart (like a beam bunched with $f_{RF} = 2\ f_{rev}$) and a *single* PU, the sum signal of the 1$^{st}$ harmonic would also cancel. Analysing the 2$^{nd}$ harmonic, the signals would add up constructively (the phase difference would be given by $h_{Schottky} \cdot 180° = 360°$). In the multi-particle case, due to the bunch intensity differences and the lack of perfect symmetries of the longitudinal particle distribution the discussed constructive and destructive effects are reduced. The signals will add up constructively on all n$\cdot h_{RF}$-harmonics (n is integer), but destructively only to some extent on all others. It is worth to note that the beam bunched at e.g., $f_{RF} = 4\ f_{rev}$ will have strong coherent signals at 4$^{th}$, 8$^{th}$, 12$^{th}$, … harmonics of the revolution frequency, and low, still non-zero signal at other harmonics. Figure 5 shows the relative amplitude of the central satellites for a beam bunched at $f_{RF} = 4\ f_{rev}$ measured in the CERN

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ELENA ring. In Schottky monitoring systems with large coherent signal contribution (like LHC Schottky Monitor [5]) the dynamic range of the measurement system may limit the observation of the non-coherent Schottky sidebands and exploiting this effect as a mitigation technique might be considered.

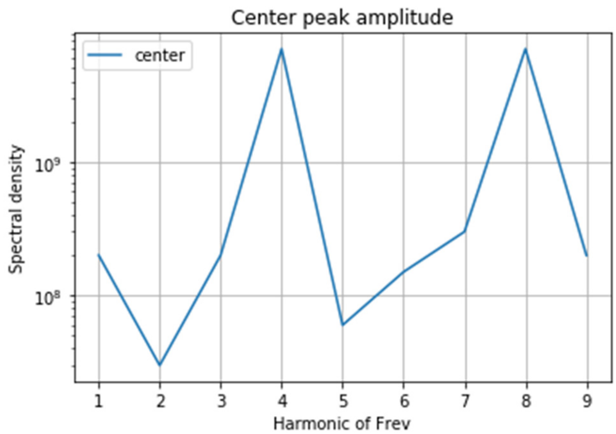


Figure 5: Relative amplitude of the central satellite in a bunched ($f_{RF} = 4\ f_{rev}$) longitudinal Schottky spectrum as a function on the observed Schottky harmonic.

## CONCLUSION

A substantial SNR improvement of the longitudinal Schottky signal has been implemented and successfully achieved on the ELENA ring. The technique uses signals from several distributed PUs in a ring that are phase-compensated before being summed and presented as frequency domain Schottky spectrum. It provides, as expected, superior performance compared to the power-spectral density (PSD) averaging of a single beam pickup. The values required for the phase compensation were calculated from the knowledge of the relative physical location of the PUs in the ring, and validated by cross correlation between sampled data from individual PUs. Cable lengths between PUs and the acquisition system were included as necessary and cable length differences minimized. Unwanted interference/spur if uncorrelated will be reduced. The presented method is implemented as an extension to the existing CERN ELENA orbit measurement system. It uses the same PUs and acquisition system, and can operates as follows: Measuring the orbit when the beam is bunched and performing the longitudinal Schottky analysis when the beam is un-bunched during cooling at fixed energy or operating on the same harmonic of $f_{rev}$ for orbit and Schottky monitoring.

## ACKNOWLEDGEMENTS

Thanks to F. Pedersen for ideas and inspiration on the summing of Schottky signals and to J. Molendijk for support on the VXS-DSP-FMC carrier.

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