BEAM SHAPING USING A NEW DIGITAL NOISE GENERATOR

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A novel digital rf-noise generator [1,2] was used to excite the COSY-beam [3] longitudinally at a certain harmonic of the revolution frequency. Rectangular shaped noise spectra with bandwidths of the order of 10 kHz and frequency resolution of about 6 Hz were used. Beam distributions were measured during shaping and after switching off the noise source in dependence of bandwidth and amplitude of the rf-noise.

I. INTRODUCTION

The application of specifically shaped noise covers a variety of important investigations in accelerator physics, such as beam transfer measurements [4], sensitive measurements of longitudinal beam aperture, controlled beam heating for electron cooling [5] as well as for ultra slow extraction (USE) [6]. The idea behind USE is to move the beam across the resonance by a diffusion process. Firstly, precisely shaped narrow band noise centred on a harmonic of the revolution frequency will be used to transform the initially Gaussian-like distributed beam into a rectangularly shaped distribution. Secondly, to drive the beam towards the resonance, band limited noise, permanently covering the extraction resonance, will be slowly moved across the previously shaped beam distribution. This causes the particles to undertake a random walk within the noise bandwidth thereby filling up any void in longitudinal phase space. Particles reaching the resonance will be extracted from the circulating beam.

II. THE DIGITAL RF-NOISE GENERATOR

Several methods exist to create band limited noise signals. With one exception [7], where the noise spectra are created digitally and a double balanced analog rf mixer is used to convert to the desired revolution harmonic, analog components have been used to build up noise sources. Also, tuneable high quality analog filters are included to reject unwanted frequency components in the spectra [8].

At COSY a new noise generator [1,2] basing completely on digital signal processing technology has been developed. The principal idea bases on the fact that the sequence

$$x(n) = \frac{1}{N}\sum_{s=0}^{N-1} \hat{x}(s)e^{-i2\pi sn/N} \qquad (1)$$

represents a complex pseudo random sequence if the random amplitudes $\hat{x}(s)$ are given. For the case of band-limited noise the amplitudes are chosen to be $\hat{x}(s) = Ae^{-i\varphi(s)}$ for $s_- \le s \le s_+$, otherwise zero, with phases $\varphi(s)$ uniformly distributed within the interval $[0,2\pi[$. The constant A is related to the desired discrete power density $S(f) = A^2/(N^2\,\Delta f)$ at frequency $f = s\Delta f$ with frequency resolution $\Delta f = 1/(N\Delta t)$. It can be shown [9] that for a sufficiently large sample length N and small Δf the real or imaginary part of the noise signal, eq. (1), has a nearly Gaussian distribution with zero mean. By applying appropriate trigonometric identities to eq. (1), the real part of the complex noise signal, $x_R(n)$, with a band-limited spectrum centered at frequency f_0 equals to

$$x_R(n) = A\left\{\cos(2\pi f_0 n\Delta t+\Theta_-(n)) + \cos(2\pi f_0 n\Delta t+\Theta_+(n))\right\} \quad (2)$$

where the phase sequences $\Theta_-(n)$ and $\Theta_+(n)$ are determined from eq. (1). Thus the noise sequence consists of two phase modulated sequences which can be created by two numerically controlled oscillators (NCO) as shown in the block diagram, fig. 1. Two digital signal processors (DSP) are used to precalculate the desired phase sequences $\Theta_-(n)$ and $\Theta_+(n)$ off-line. The outputs of the NCOs are added and fed to a DAC that produces the analog noise signal. This corresponds to multiply the real signal following from eq. (1) or (2) by the low pass filter transfer function of the DAC.

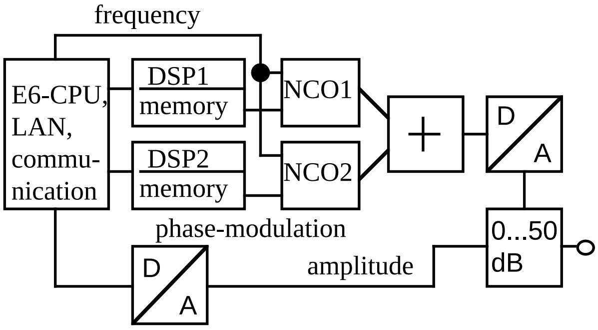

Fig. 1: Lay-out of the noise generator

To achieve a frequency resolution down to 6 Hz, each DSP is linked to a fast local memory bank of 2Mx16 bit size with an access time < 20 ns for storing the phase sequences. A fast sequencer transfers the phase sequences in real time to the NCOs. The clock frequency of 50 MHz allows together with a 32 bit frequency word an adjustment of the center frequency f_0 in 11.6 mHz steps.

The design offers the possibility to tailor sharply band-limited noise spectra of arbitrary shape at center frequencies up to 20 MHz. High resolution components guarantee signal-to-noise ratio better than 60 dB. The bandwidth can be chosen in the wide range from 1 kHz up to 100 kHz. Typical roll-off characteristics of the order of 180 dB/octave are achieved. Two independent digital noise generators are available. Both allow to control the amplitude of the signal and can be triggered by COSY-Control. One module is capable to deliver swept noise with controlled speed < 1 kHz/s. The complete digital design makes the circuit completely predictable, including finite bit resolution. The design has been applied for a patent [10].

III. EXPERIMENTAL RESULTS

Longitudinal beam shaping was studied for debunched beams in flat top of a COSY cycle with approximately one minute flat top length. The experimental test set-up is shown in figure 2.

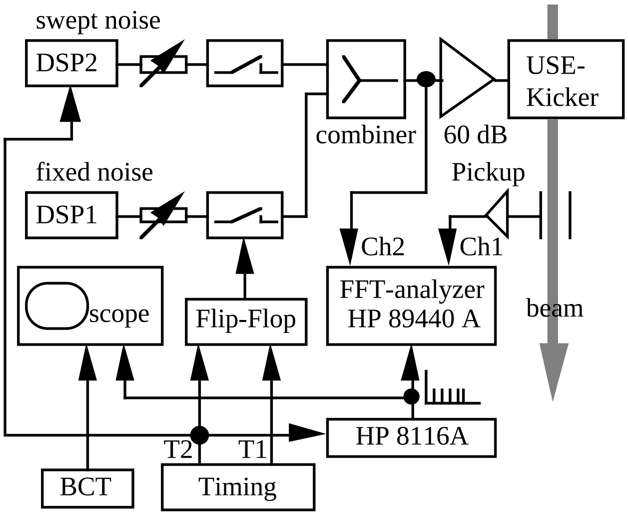

Fig. 2: Experimental test set-up

The timing system delivers two time signals to start (T1) and to stop (T2) the fixed noise (DSP1) for shaping via a Flip-Flop. To measure the beam distribution after applying the noise, the stop signal T2 starts the puls generator HP8116A delivering a preset number of pulses which define the instances at which a spectrum is taken by the FFT-analyzer. During the whole cycle the beam current transformer (BCT) as well as the pulses of the HP8116A could be monitored on a scope. By interchanging T1 and T2 measurements during heating were also possible. Swept noise could be applied after shaping by starting DSP2 with trigger T2. Both noise generators could be controlled via a workstation. The combined output of the noise generators was fed to a longitudinal kicker [11] after power amplification.

The response of the beam to the longitudinal excitation was observed with a beam position monitor of COSY [12] in common mode operation. In addition, the beam current was monitored to adjust the noise bandwidth so that no particle losses could occur during beam heating. Figure 3 to 5 show Schottky scans around the third harmonic of the revolution frequency with 5 dB/div and 10 kHz span after 10 s noise excitation for different noise amplitudes. Note, that the upper lines appearing in the figure are due to interference frequencies and are not affected by the noise. The rectangularly shaped noise spectrum of width 4 kHz was centred at the fourth harmonic so that the third harmonic reflects the beam distribution. Figure 3 shows the undisturbed beam spectrum (amplitude 0). The figures demonstrate that the beam shape becomes flattened with increasing noise amplitude. The beam spectrum attains a width of 3 kHz (Fig. 5) as expected according to the equation $\Delta f_m = (m/n) \cdot \Delta f_n$ where n is the harmonic number at which the noise of bandwidth Δf_n is applied and m denotes the harmonic at which the beam is observed. In this case m = 3 and n = 4.

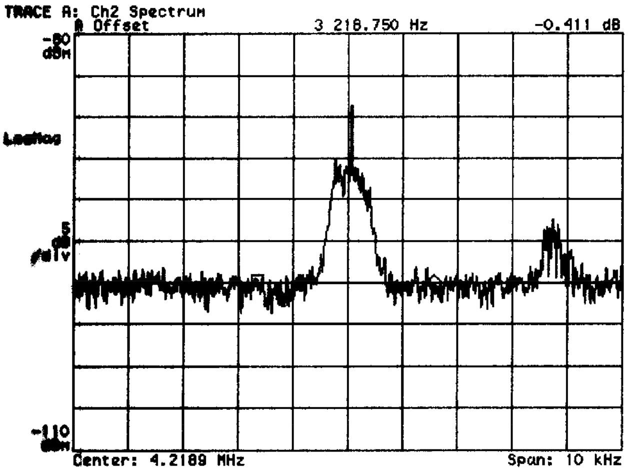

Fig. 3: Schottky scan of the undisturbed beam observed at the 3rd harmonic, 4.219 MHz.

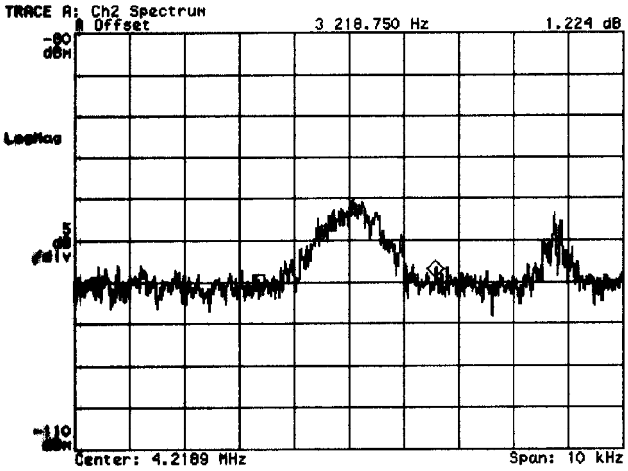

Fig. 4: Schottky scan observed at the 3rd harmonic after shaping with amplitude 2.

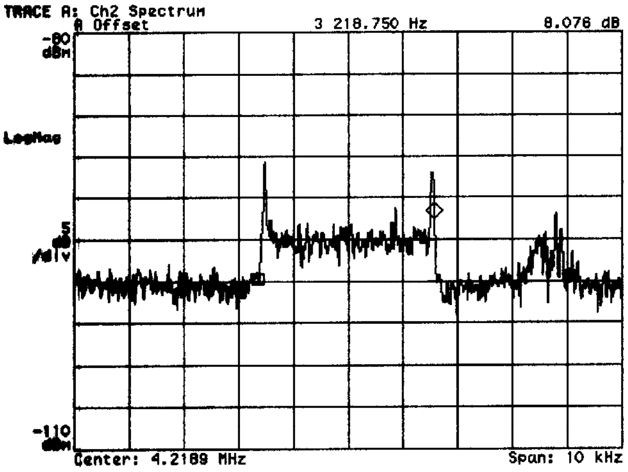

Fig. 5: Schottky scan observed at the 3rd harmonic after shaping with amplitude 8.

The spectrum in fig. 5 is dog-eared indicating an enhancement of particles near the boundary of the distribution. Random walk simulation show that this is due to the sharp edges of the exciting noise spectrum. This enhancement can be reduced by flattening the sharp roll-off of the noise spectrum. On the other hand the sharp edges could be of advantage for fine longitudinal acceptance measurements. In further tests, noise of constant amplitude but different durations had been applied. From this the expected role that duration times amplitude is constant could be derived.

Figure 6 (5 dB/div, span 10 kHz) shows the Schottky scan of the beam distribution at the first harmonic, 1.239 MHz, after 10 s asymmetric noise excitation. The beam was excited at the fourth harmonic, 4.956 MHz, with rectangular shaped noise with a bandwidth of 6 kHz. However, the centre was shifted upwards by 3 kHz.

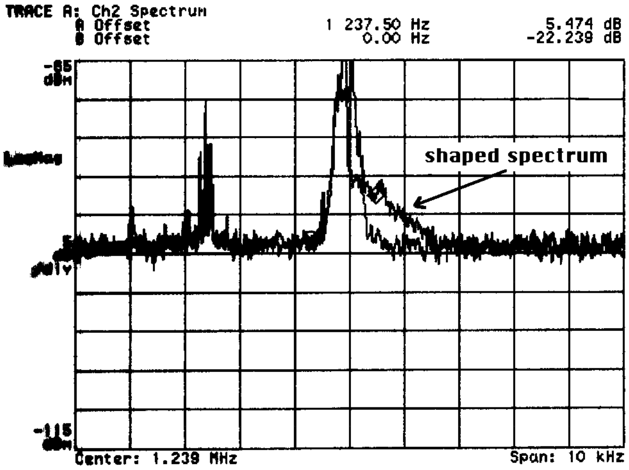

Fig. 6: Schottky scan around the revolution frequency after shaping with 6 kHz noise bandwidth around the 4th harmonic. The noise centre is shifted by +3 kHz.

As expected only particles lying in the right handside of the distribution diffuse into the range of higher momenta. For comparison the figure also contains the spectrum of the undisturbed beam distribution. The low lying lines in the spectrum correspond to interference frequencies.

IV. CONCLUSIONS

The novel narrow-band digital noise generator could be successfully applied for controlled beam shaping. Previous longitudinal beam transfer function measurements [4] using the novel digital rf-synthesizer to excite the beam yielded equivalent results as obtained by applying an analog noise source. This confirms the result following from the current measurements that a frequency resolution of about 6 Hz seems to be sufficient for longitudinal beam shaping applications at COSY. Indeed, a controlled diffusion was observed. It was demonstrated that the diffusion coefficient could have been influenced by the amplitude of the applied noise. Depending on the duration of the excitation and due to the sharp cut-off of the noise spectra the resulting beam distributions exhibit a steep slope of the edges superimposed with sharp spikes. Thus, stepping the bandwidth of the excitation noise would allow a fine probing of the longitudinal acceptance of the machine. Improved tailored noise spectra for shaping and swept noise spectra to move the shaped beam towards the resonance will be included in the final USE-system at COSY. In order to keep shaping time short low noise amplifiers have to be incorporated.

Finally, due to its completely digital stages the new noise generator outperforms conventional generators in accuracy, stability, tuning range/bandwidth/speed, resolution and signal modulation performance. It is thus not only of interest in accelerator physics but also in the field of communication techniques.

V. REFERENCES

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