APPLICATION OF DIGITAL NARROW BAND NOISE TO J-PARC MAIN RING

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Abstract

Applying narrow band noise to the beam in J-PARC Main Ring (MR) in flattop, while the acceleration voltage is off helps to counteract the effect of magnetic field ripple on the slow extraction. For this purpose, a complex noise sequence provided by a DSP modulates a custom made DDS synthesizer to create single sided spectra with suppressed carrier.

The noise is calculated starting from a description in frequency domain. An algorithm creates narrow band spectra with optimized behavior in time domain. Frequency domain data is transformed to time domain, and the amplitude is smoothed. The smoothed data is transformed back to frequency domain, and the spectral shape is restored. This process repeats until the amplitude in time domain has converged, while the desired spectrum shape is preserved. Noise generated in this way can be tailored for different requirements.

We explain signal properties, hardware, and preliminary beam test results, when the noise is applied a) to the MR RF system, and b) to the horizontal exciter system.

NOISE SYNTHESIS

Slow extraction [1] from MR to the Hadron hall is based on a 3rd order resonance and ramping the tune during the extraction process. The magnet ripple causes a tune variation in the order of ±0.003 and leads to unwanted intensity fluctuations of the spill [2].

Influenced by stochastic extraction experience [3, 4], narrowband noise was created and applied to the beam to reduce the effect of the ripple and to increase the duty factor, defined as (Average spill /RMS spill)^2, where the spill is collected in time bins, here at 10 μs rate.

In contrast to white noise, the signals prepared for application to the beam have a well-defined limited bandwidth [5]. Following [6], first the desired shape of the pseudo-noise is defined in the frequency domain. At a modulation sample rate of 20 kHz, a sequence length of 65536 points results in a noise sequence duration of 3.2768 s. Then in frequency domain the carrier spacing is approximately 0.305 Hz. The example in Fig. 1 is a 12 Hz wide rectangular shaped spectrum containing 40 non-zero carriers with index *i* from 0 to *mB*=39. These are taken as fixed amplitude values *A[i]* for a set of oscillators in frequency domain. The initial phases of these oscillators *Phi[i]* are set as random in the interval [0, 2π). As shown in Fig. 2 this set of oscillators is summed up as In-phase and Quadrature-phase (I/Q) components. This gives a complex modulation sequence in Cartesian coordinates that is translated to polar coordinates (amplitude, phase) by a coordinate transformer. This is equivalent to a modulated single oscillator. When this complex modulation information is up-converted by a mixer with ideal modulation capabilities at given local oscillator frequency, a single side band (SSB) spectrum appears.

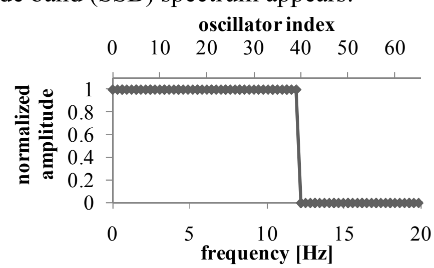

Figure 1: Example of a 12 Hz wide noise band

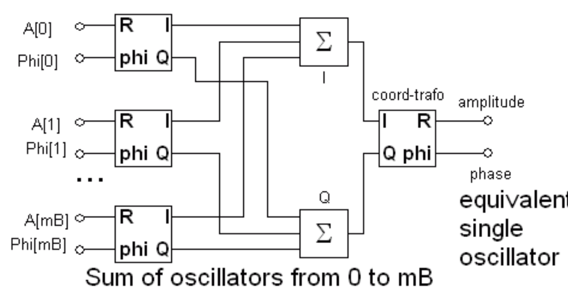

Figure 2: Calculation principle

The amplitude (in time domain) of this noise shows a variation that can be characterized by an amplitude duty-factor, defined as (Average amplitude /RMS amplitude)^2. From viewpoint of a power amplifier, driving the system that influences the beam, it is advantageous, if the peak power is not much higher than the average. For true random noise, this is difficult to handle, but for digitally generated noise, this can be achieved. Fig. 3 describes the iteration process that smoothes the noise amplitude in time domain.

The initial polar data is changed to Cartesian for FFT to time domain. In time domain the instantaneous amplitude is normalized by multiplying with a scaling factor. This distorts the spectral properties. This data is transformed to frequency domain and the amplitude of the spectrum is corrected. The data is transformed back to time domain. If the amplitude duty factor in time domain is high enough, or the iteration limit is reached, the process finishes and the data is saved. The free parameter is the phase. The process converges so that the power spectrum in frequency domain is kept as expected, while the amplitude variation in time domain is minimized. On a 3 GHz dual core PC, this takes roughly 2 minutes.

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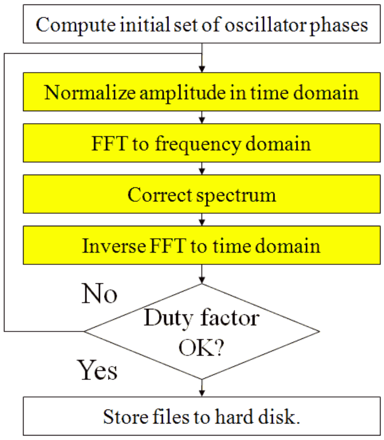

Figure 3: Iterative optimization process

Fig. 4 shows the amplitude histogram in time domain for a 12 Hz wide noise after 1, 100, and 5000 iterations. The converging of the amplitude properties is shown in fig. 5. The amplitude duty factor increases from initially 0.8 to 0.9777. The ratio of average to maximum amplitude increases from 51.4% to 73.2%, and the ratio of average to maximum power improves by a factor of 2 from 26.4% to 53.7%. For selected bandwidths up to 5 kHz after 5000 iterations, Table 1 shows the power ratio.

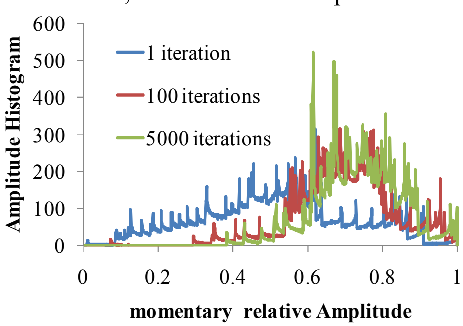

Figure 4: Amplitude Histograms as function of iteration

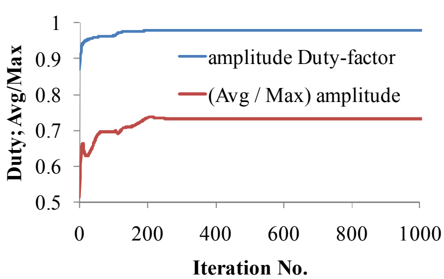

Figure 5: Amplitude properties as function of iteration

Table 1: Avg. / Max. power as function of bandwidth

Bandwidth [Hz]	250	500	1000	2500	5000
Avg./ Max power	50%	49%	47%	43%	44%

SIGNAL GENERATOR HARDWARE

The signal generator schematic is shown in fig. 6. It is based on a custom Compact PCI DDS system running at 80 MHz clock that is modulated in amplitude and phase by a commercial DSP board.

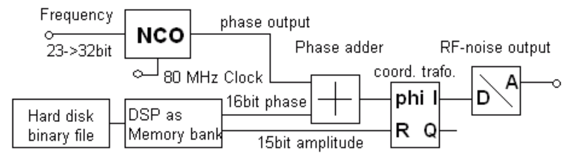

Figure 6: Narrow-band Noise generation hardware

The frequency is given in 23 bit, so that the left edge of the spectrum can be set from 500 kHz to 10 MHz with approximately 0.839 Hz resolution. The 16 bit phase modulation is equivalent to 2π. The amplitude resolution is 15 bit. If the modulation were used as is at 20 kHz rate, the noise spectrum would have unwanted mirrors at multiples of the 20 kHz sampling rate left and right of the carrier. Therefore the DSP interpolates the 2^{16} points by a factor of 16, increasing the effective rate to 320 kHz. Then the highest unwanted sidebands are located further away from the center frequency at ±320 kHz. For 16x linear interpolation of a 1 kHz wide noise, Fig. 7 shows the highest sidebands −54 dBc below the center peak at 1.7205 MHz. Also weaker sidebands at −240, +80, and ±20 kHz offset are seen. Especially the sidebands at ±20 kHz are reduced (see fig. 8a) by 11 dB with FFT interpolation instead of linear interpolation. There the 2^{16} complex points are transformed to frequency domain and extended to 2^{20} by zero padding. Transforming back to time domain gives 2^{20} up-sampled and filtered points at 320 kHz rate. The DSP needs approximately 20 s and 8 (of 16) MB RAM for this. Fig. 8b shows the SSB spectrum at 10 kHz span. The left edge at 1.7205 MHz is *f(h=9)* for MR in the 30 GeV flat-top.

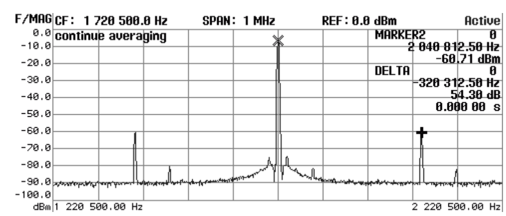

Figure 7: 1kHz wide noise with 16x linear interpolation

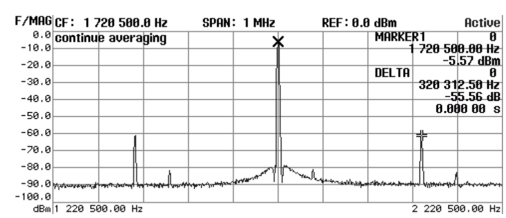

Figure 8a: 16x FFT interpolation. 1 MHz span

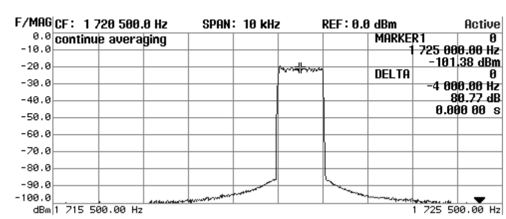

Figure 8b: 16x FFT interpolation. 10 kHz span

EXPERIMENTAL RESULTS

Longitudinal noise

With the setup in fig. 9 longitudinal noise was applied to the MR beam in flat-top at 30 GeV. A directional coupler inserted into the signal path of the LLRF system to the driver amplifier of MR cavity #5 minimizes the influence on normal accelerator operation. In flat-top a P3 trigger activates the noise amplitude ramp. This way, the LLRF signal for acceleration and the synthesized noise share the same cavity. The well-defined noise sequence maximum limits the peak cavity voltage to 4 kV independent of bandwidth setting, thus preventing the risk of overvoltage. For *(h=9)* at 1.7205 MHz, a bandwidth of 12 Hz was chosen. In order to obtain sufficient time and frequency resolution the harmonic *(h=909)* at 173.7705 MHz was observed with a RSA3303A spectrum analyzer connected to a Wall-current monitor.

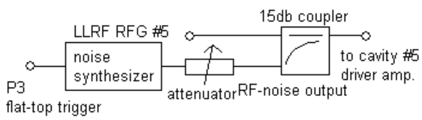

Figure 9: Connection to MR cavity #5 system

Longitudinal beam spectrograms for near zero chromaticity at noise levels of 0%, 50%, and 100% relative to 4 kV during extraction are shown in fig. 10. In fig. 10a, in the beginning the spectrum width corresponds to the momentum spread. During the resonant extraction process the particle distribution shrinks. In fig. 10b the longitudinal noise has some effect, but according to fig. 11 the duty factor is not improved. In fig. 10c the longitudinal noise results in a spectrum that is wider than expected from 101*12=1212 Hz, so further study and simulation are necessary to understand. Fig. 11 shows the duty factor as function of noise level. In average the duty factor improved from 8.4% (noise off) to 11.4% (noise 100%). For non-zero chromaticity, the duty factor improved from 15.7 % (noise off) to 19% (noise 100%).

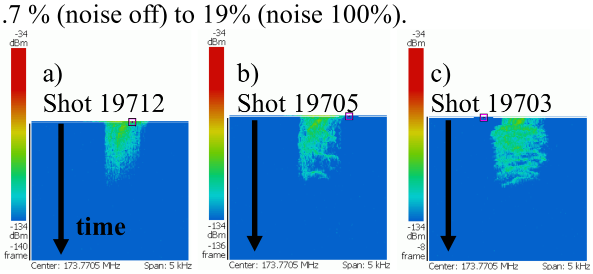

Figure 10: longitudinal spectra. a) 0%, b) 50%, c) 100%

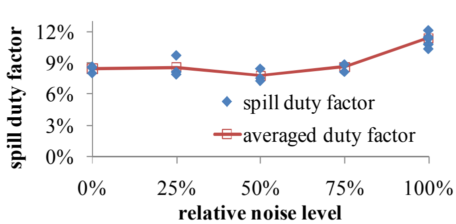

Figure 11: Extraction duty factor vs. noise level

This study confirms that 12 Hz noise bandwidth was too narrow. Thus particles that experienced the noise for a short time before extraction might have seen the noise as a coherent signal. Therefore it is better to use a higher harmonic, which allows a broader bandwidth.

Transversal noise

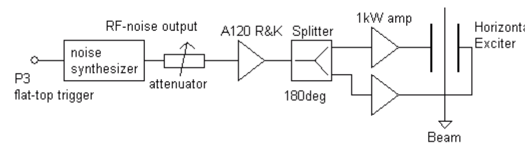

Figure 12: Experimental setup for transversal noise

Fig. 12 shows the setup for transversal noise. The idea is to grow the amplitude of the circulated beam by a transverse rf field to push the amplitude dependent tune to the resonance. During the MR beam study in Run #30, noise bandwidths from 250 to 1000 Hz were applied. The duty factor was increased from 9% (noise off) to 15% (noise on). More details in [7]. The center frequency was set to 5.033877 MHz *(h=36)* with 1 kHz wide noise at 1 kW maximum power and slightly less than 500 W average power for each of the amplifiers driving the exciter.

SUMMARY AND OUTLOOK

We present a narrow band digital noise generator that has helped to improve the duty factor of the slow extracted MR beam at 30 GeV.

The emphasis in the future is probably the usage for transversal beam application. When narrow band noise is routinely used in beam operation, the custom digital hardware can be upgraded to a commercial signal generator with built-in vector modulation capabilities.

Also it is interesting to study the effect of longitudinal noise with wider bandwidth. In the summer shutdown 2010 we plan to install a second harmonic *(h=18)* cavity into Main Ring. Then it becomes possible to apply noise with wider bandwidth compared to *(h=9)* cavities.

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