Simulation of narrow-band longitudinal noise applied to J-PARC Main Ring

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Abstract

In MR extraction studies in the beginning of 2010, the application of narrow band longitudinal noise to the MR-beam at 30 GeV in flat-top to increase the duty factor of the extracted spill was tested. The longitudinal spectrum with noise became wider than expected from the bandwidth of the band-limited noise. Here we show longitudinal beam simulations, using the same digital noise that was applied to the beam, to understand the measured spectra. This also allows to estimate, which would be good combinations of harmonic number, bandwidth and amplitude of the noise to obtain a desired beam shaping.

J-PARC Main Ring用のnarrow-band longitudinal noiseシミュレーション

1. Introduction

In MR extraction studies in the beginning of 2010, the application of narrow band longitudinal noise to the MR-beam at 30 GeV in flat-top to increase the duty factor of the extracted spill was tested [1, 2]. The 12 Hz wide noise was defined in frequency domain by a set of 40 oscillators with approximately 0.305 Hz spacing as shown in fig.1.

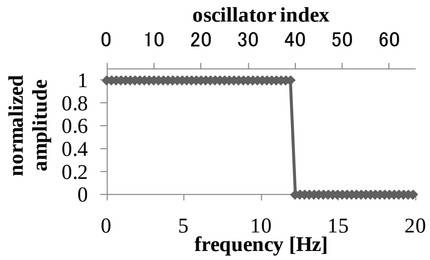

Figure 1: 12 Hz wide noise in baseband.

The amplitude histogram of the noise, which was optimized by an FFT algorithm [3], is shown in fig. 2.

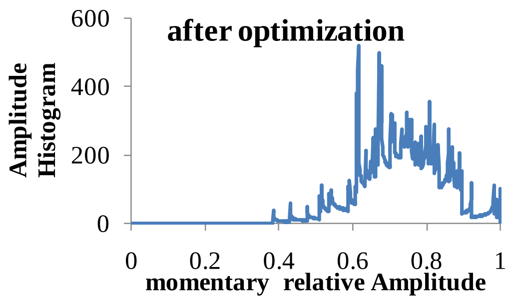

Figure 2: Amplitude histogram of 12 Hz wide noise

The noise is defined as a complex signal with (I, Q), e.g. In-phase and Quadrature-phase components. Therefore it can be shifted in frequency as single-side-band (SSB) signal, when it modulates a carrier. Instead of (I, Q), the synthesizer was modulated with an equivalent combination of amplitude and phase, shown in figs. 3 and 4.

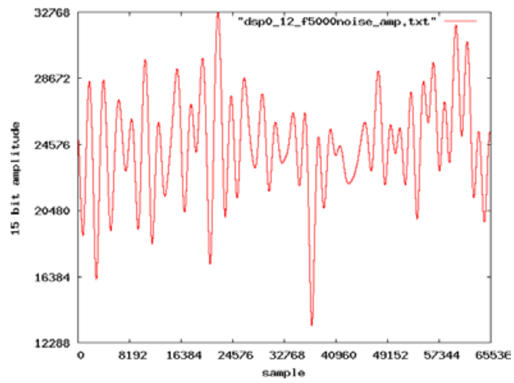

Figure 3: 12 Hz noise amplitude modulation sequence

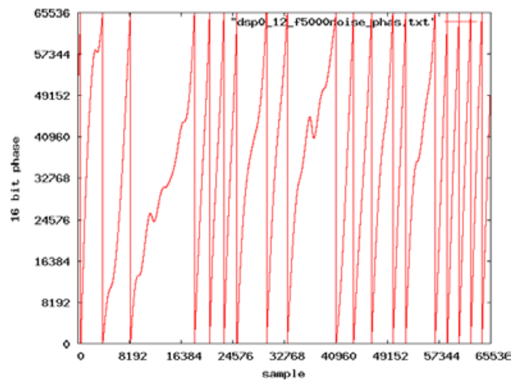

Figure 4: 12 Hz noise phase modulation sequence

In the experiment, a carrier of 1.7205 Hz was modulated with this noise, resulting in a noise band from 1.720500 Hz to 1.720512 Hz. This covers the longitudinal beam spectrum at (h=9) for 30 GeV kinetic energy.

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2. Longitudinal Beam experiment

A schematic of the noise generator used during the experiment is shown in fig. 5. The chosen frequency is in the range of (*h*=9) of the MR acceleration cavities. The connection to MR cavity system #5 was done according to fig. 6.

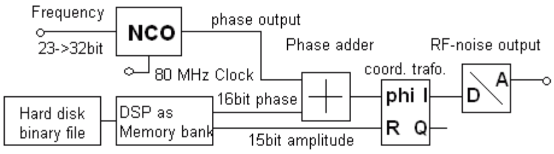

Figure 5: Narrow-band noise generation hardware

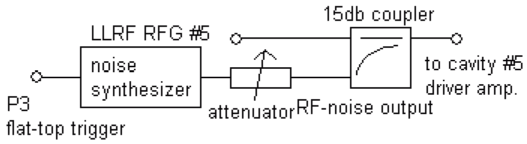

Figure 6: Connection to MR cavity #5 system

The longitudinal spectrum was recorded with a real-time FFT spectrum analyzer connected to an MR wall-current monitor. The revolution frequency at 30 GeV is approximately 191.166 kHz. At lower multiples of the revolution frequency, e.g. (*h*=9, 18, 27 … 90) it is not possible to acquire a spectrogram with both sufficient time and frequency resolution. Also there is some cross-talk from unwanted signals, which can be seen by the FFT analyzer. Scanning multiples of (h=n·90) and also (h=n·90 + 9) finally the higher harmonic (*h*=909) was chosen. Each spectrum length is 128ms and the spectrum interval 32ms. The center frequency was 173.7705 MHz and the span 5 kHz with 15.66 Hz NBW. The data was stored to the local analyzer hard-disk and later processed by the corresponding offline RSAVu application. Both noise synthesizer and FFT analyzer are triggered by the P3 flat-top trigger. The effect of the synthesized noise from 1.7205 to 1.720512 Hz applied to the beam at (*h*=9) is expected to be found at (*h*=909) starting from 173.7705 MHz with a width of 12·101=1212 Hz.

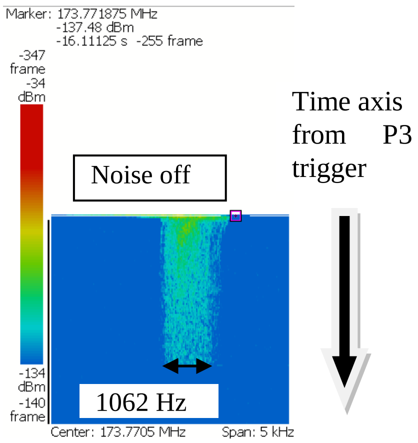

Figure 7a: Shot 19729 with noise off

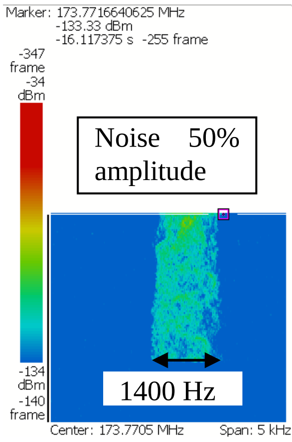

Figure 7b: Shot 19727

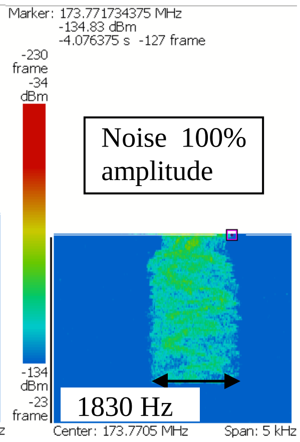

Figure 7c: Shot 19726

The longitudinal spectrogram of shot 19729 in fig. 7a was taken with noise off. In Fig. 7b the noise amplitude was 50%, e.g. a peak voltage of 2 kV, and in fig. 7c 100% amplitude (4 kV peak) was applied. At 50% noise level, the longitudinal spectrum almost matches to the noise width. At 100% noise level the longitudinal beam spectrum width of 1830 Hz is much wider than expected. In both cases with noise on, one can see a wave like structure going down inside the spectrogram, indicating that the effect of the noise contains a coherent component.

3. Longitudinal ESME simulation

3.1 Preparing the simulation code

In order to understand how the noise interacts with the beam, a longitudinal simulation with ESME [4] was prepared. However, several programming issues with the recent 2009_3 version were found, therefore the older 2004 (Fortran77) version of ESME was used. In order to process the noise modulation patterns "as is", the limit of the curve points was raised to 70000, resulting in an 8-fold increase of the executable size to 64MB. As the phase curve was ignored, when a frequency curve was active, the phase modulation in fig. 4 was translated to an equivalent frequency modulation shown in fig. 8. Tracking 10^5 particles for 2.8s needs 4 hours on a 3 GHz CPU. With a recent Quad core I7-930, one simulation needs 87min, while up to 8 simulations can run in parallel.

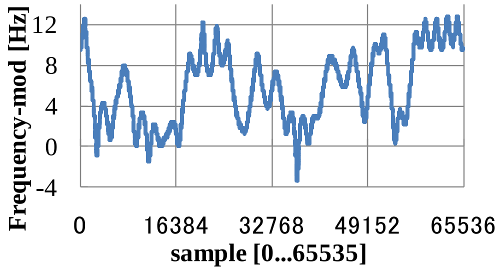

Figure 8: equivalent frequency-modulation

3.2 Simulating the MR beam in flat-top

The simulation of the situation "noise off" is shown in fig. 9. E_{rms} at simulation end (2.816s) is 34.1 MeV.

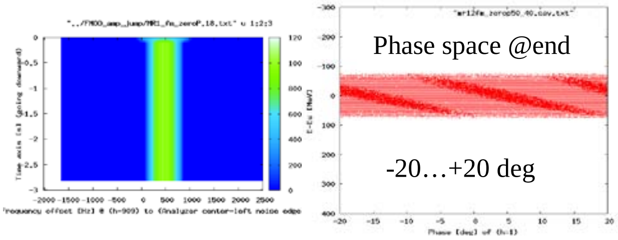

Figure 9: (left) Spectrogram (linear scale) from beam energy. (Right) Phase space at simulation end.

The situations "noise 50%" and "noise 100%" are shown in fig. 10. The 100 ms noise amplitude ramp from 0.2 to 0.3s is denoted by an arrow. In case of 50% amplitude, E_{rms}=43.1 MeV @end, this is a 26% increase compared to noise off. In the experiment, this increase was 32%. In case of 100% amplitude E_{rms}=47.6 MeV @end, this is a 40% increase compared to noise off. In the experiment, this increase was 72%. If the noise ramp up is faster: 50µs, E_{rms} and frequency width @end are almost same, but the shape of the energy center oscillation changes, as shown in fig. 11.

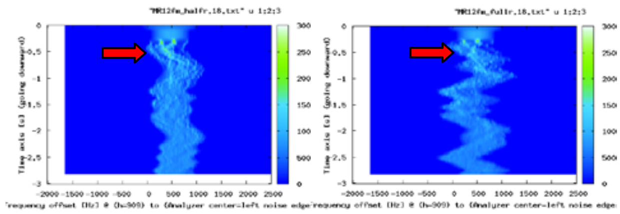

Figure 10: 50% (left) and 100% (right) noise case.

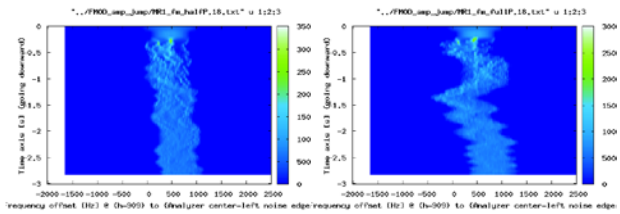

Figure 11: 50% and 100% case with 50µs noise ramp-up.

Then it was simulated when a higher harmonic is chosen with noise bandwidth scaled accordingly. Fig. 12 shows the effect of noise widths Δf=24, 36, and 48 Hz at (h=18, 27, and 36) respectively at 50% amplitude. The phase space diagrams at simulation end are in fig. 13. Fig. 14 shows these cases at 100% amplitude with the phase space diagrams in fig. 15.

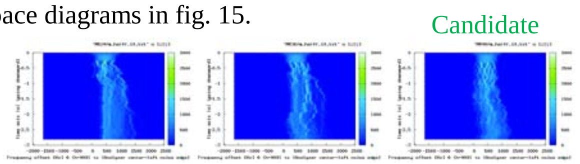

Fig. 12: Δf=24Hz Δf=36 Hz Δf=48 Hz (50%)

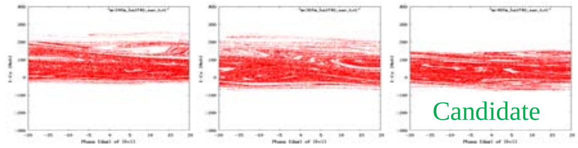

Fig. 13: Δf=24Hz Δf=36 Hz Δf=48 Hz (50%)

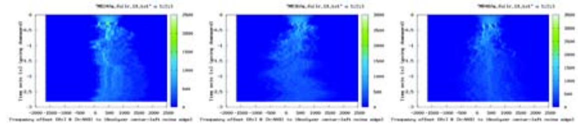

Fig. 14: Δf=24Hz Δf=36 Hz Δf=48 Hz (100%)

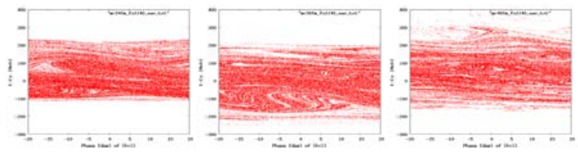

Fig. 15: Δf=24Hz Δf=36 Hz Δf=48 Hz (100%)

In all 3 cases of 100% amplitude, the unstable motion indicates that the voltage is already too high. In case of 50% amplitude the phase space at the end of simulation for the case Δf=48 Hz with (h=36) looks most smooth and the increase of E_{rms} is only 50%, compared with 80% for Δf=24 Hz and 75% for Δf=36Hz. So this might be a good candidate.

4. Summary and outlook

In extraction studies, narrow band longitudinal noise was applied to the MR-beam at 30 GeV flat-top. The longitudinal spectrum with noise at higher amplitude became wider than expected. Longitudinal beam simulations, using same digital noise, confirm that the beam spectrum gets wider than (noise width x harmonic ratio) at higher amplitude. Simulations can help to find candidates as combinations of harmonic number, bandwidth and amplitude of the noise to obtain a desired beam bandwidth, while minimizing the center energy oscillation where the beam sees the signal as mix of "noise" and coherent signal. Still, the simulations do not reproduce all details; therefore the study will be continued also with other tracking algorithms.

References

[1] A. Schnase et al., "Application of Digital Narrow band noise to J-PARC Main Ring", IPAC10, Kyoto, TUPEA051

[2] Masahito Tomizawa, et. al, "Status and Upgrade Plan of Slow Extraction from the J-PARC Main Ring", IPAC10, Kyoto, THPEB014

[3] A. Schnase, "Narrowband Noise signals with minimized amplitude variation", LLRF 09 workshop, Tsukuba, 20th October 2009, TP20

[4] ESME homepage: http://www-ap.fnal.gov/ESME/