ELIMINATION OF HIGH FREQUENCY NOISE FROM THE BEAM IN THE DIAMOND LIGHT SOURCE STORAGE RING

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Abstract

High frequency beam motion has been identified as a source of noise in infrared beamlines in a number of synchrotron light sources. Diamond is a third generation synchrotron light source with storage ring current maintained by two superconducting CESR-B cavities powered by IOT-driven RF amplifiers. In our case, undesirable beam motion in the kilohertz range is predominantly driven by spectral content in the voltage across the IOTs arising from the switched mode nature of the high voltage power supply. Spectral noise on the amplifiers and beam has been identified and characterised and efforts to eliminate this noise are described. Care has been taken to maintain the overall stability of the RF at Diamond and tests have been carried out on an infrared beamline to investigate the degree to which beam noise impacts beamline operation in its different operating configurations.

HIGH POWER AMPLIFIERS FOR THE STORAGE RING RF SYSTEM

Diamond is a 3 GeV third-generation light source. The SR RF straight is designed to accept up to 3 superconducting 500 MHz cavities similar to those used on CESR [1]. Currently two cavities are installed each connected to a 300 kW amplifier [2] and an analogue LLRF system.

The high-power amplifier system was supplied by Thales Broadcast and Multimedia, now Ampegon, and generates the maximum power of 300 kW in each amplifier by the combination of four IOTs in a waveguide combiner system similar to that used for very high power TV transmitters [3]. A schematic drawing of the IOT combination is shown in Figure 1.

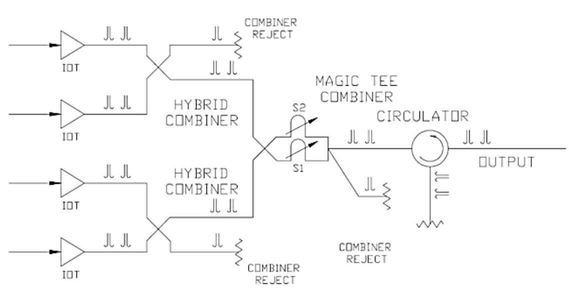

Figure 1: IOT combination scheme used in each of the Diamond 300 kW amplifiers.

The IOTs used are 80 kW IOTD2130 tubes from E2V Technologies. All four IOTs for each amplifier are fed from a single High Voltage Power Supply (HVPS). The HVPS is based on Ampegon Pulse Step Modulation (PSM) technology in which multiple series-connected switched mode power supply modules are switched by IGBT transistors in a process of Coarse Step Modulation (CSM) of multiple modules and Pulse Width Modulation (PWM) of individual modules in order to maintain a constant voltage across the IOTs [4]. There are 64 modules in each Diamond HVPS, each configured to generate 750 V, ensuring redundancy of modules at the Diamond operating voltage of 35 kV. This redundancy allows the amplifier to continue operating in the event of a failure of one or more modules, and the rotation between the multiple modules is designed to load each module equally to ensure maximum component lifetime.

The output of the HVPS is filtered to reduce the PSM switching noise on the IOTs, but nevertheless traces of the modulation can be seen on the beam, and this has been found to pollute beamline measurements at other synchrotrons operating with similar HVPS systems, particularly on the infrared beamlines at the Swiss Light Source, which operates with klystron tubes and normal conducting cavities with much lower quality factor than the CESR cavities at Diamond [5].

MEASUREMENT OF BEAM NOISE

The fundamental frequency of the module rotation noise is dependent on the PWM frequency, and can be defined as a multiple of the internal reference frequency of 3125 Hz by a user-defined parameter, *N*, and by the number of operating power supply modules, *M* according to

$$f_{rot} = \frac{N+1}{M} \times 3125\,\text{Hz}.$$

Transverse beam motion in Diamond can be monitored using any one of the Libera Electron Beam Position Monitors (BPMs) located around the storage ring [6]. A simple FFT of the horizontal beam position taken over an extended period of user operation, shown in Figure 2 shows a surprisingly rich spectral content in the accessible range from zero to 5 kHz.

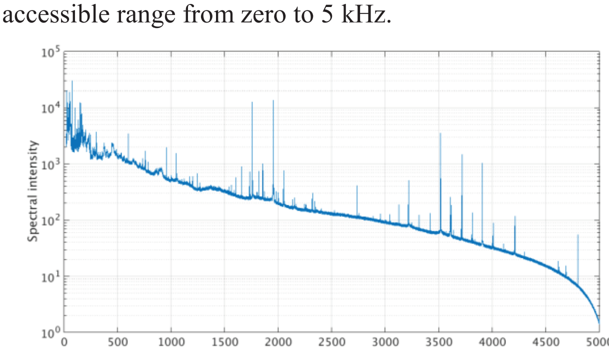

Figure 2: Noise on beam during routine operation with module rotation on.

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HVPS parameters in Figure 2 were $N = 35$ and $M = 64$, giving a nominal module rotation frequency of 1757 Hz (3514 Hz in second order). These frequencies are present in the spectrum along with many others.

Intermodulation of switching lines with mains frequency can be identified by tracking the 50 Hz mains frequency and noting that the frequency drifts are visible on the horizontal spectrum. Figure 3 is a false colour plot of horizontal beam motion overlaid with the mains frequency in red, clearly showing the correlation in frequencies.

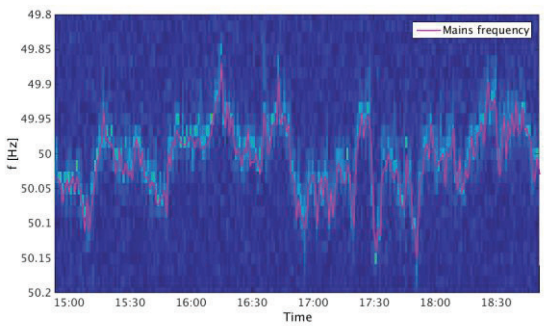

Figure 3: Observation of mains frequency on the beam spectrum.

Intermodulation lines can then be identified by correlation with mains frequency, for example in Figure 4 the line at 3118 Hz drifts with mains over a period of several hours and can be identified as a sideband of the $N = 34$, $M = 64$ second harmonic line at 3418 Hz at a frequency six times the mains below.

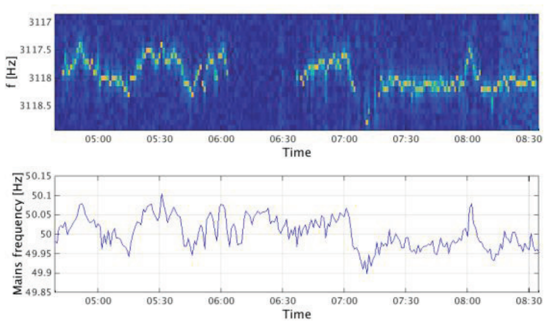

Figure 4: Horizontal beam motion (above) and mains frequency (below).

Figure 4 also shows gaps in the frequency record of the 3118 Hz line, for example between the times of 06:10 and 06:40. These gaps can be understood with reference to the upper plot in Figure 5, which shows the intensity of two lines measured over a period of several days, at 1709 Hz (blue, the fundamental $N = 34$, $M = 64$ line) and 1758 Hz (green, the fundamental $N = 35$, $M = 64$ line). It can be seen in this plot that the spectral power switches spontaneously between the two values corresponding to the different PWM parameter, N. The reason for the switch in frequency is unclear, but it is strongly dependent on the phase voltage of the incoming supply: the lower part of Figure 5 shows that power is switched from one frequency to the other when the phase voltage falls outside the 226 V to 228 V window.

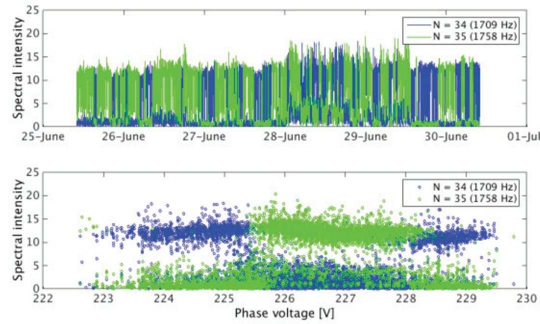

Figure 5: Relative intensity of two rotation lines (upper) and the dependence of line intensity on phase voltage (lower).

The tendency of spectral lines to jump appears to vary according to the defined N parameter, and it is possible to choose a value of N such that beam operation is possible without any uncontrolled jumps for weeks on end.

The M factor in the expression for rotation frequency above, corresponding to the number of active modules in the HVPS, can also change spontaneously, resulting in a redistribution of spectral power as shown in Figure 6, a false colour plot of horizontal beam motion around 2700 Hz over a period of 24 hours. In this case, the number of active modules was limited to a maximum of 61, but can be seen to change throughout the day to 60 and back. The figure also shows switching between $N = 50$ and $N = 51$. Again, the jumping of power between spectral peaks is dependent on the defined M value, and the number of modules appears to remain at the maximum value of $M = 64$ when all modules are brought into operation.

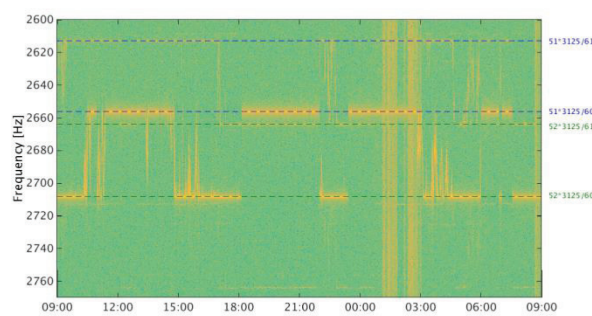

Figure 6: Intensity jumps in horizontal spectrum corresponding to changes in the number of active modules.

With the knowledge that the module rotation lines are accompanied by sidebands at multiples of the mains frequency and that the power in the beam spectrum can occasionally jump from one peak to another, all intense lines in the beam spectrum can be identified. Figure 7 shows a region of the horizontal spectrum with each line identified according to its N value and intermodulation with harmonics of mains frequency.

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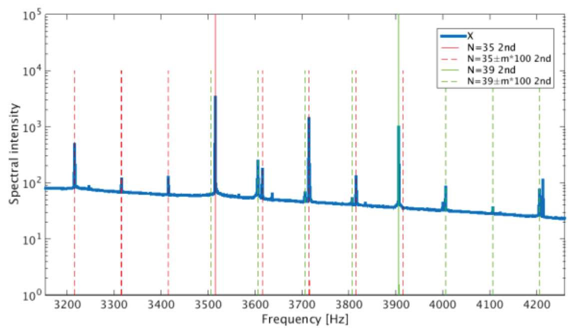

Figure 7: Detail of spectrum with all intense lines identified.

The most direct method of removing the module rotation noise is to simply stop module rotation at the HVPS. This approach has been effective at other light sources [5] and the initial test at Diamond shows that virtually all lines can be eliminated from the spectrum in the same manner. Spectra from the initial test are shown in Figure 8. Comparison of the two traces reveals that all module rotation lines have been removed and the only spectral content remaining is a number of lines arising from mechanical vibration below 2500 kHz and an intense feature at 3715 Hz. The 3715 Hz feature was audible outside the storage ring tunnel and was identified as a mechanical vibration in a water cooling pipe on the girder. Flow through this pipe has been modified and the feature is no longer there. Elimination of all other mechanical vibration of the girder is an ongoing project at Diamond.

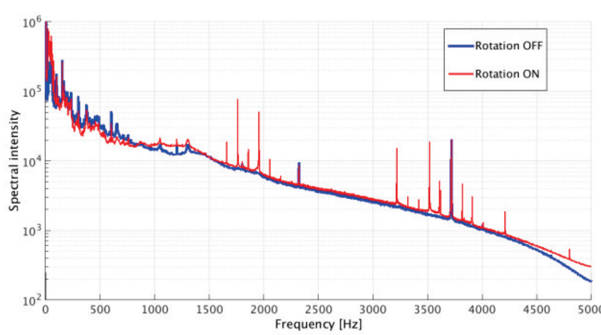

Figure 8: Spectrum of horizontal motion in beam with (red) and without (blue) module rotation.

GLOBAL STABILITY ISSUES

During the first extended test with HVPS module rotation disabled, the droop of module voltage with output current was identified as a problem. IOTs in the Diamond amplifier use current modulation to amplify RF power, and so as the output of the IOTs increases the current drawn from the HVPS increases and the HVPS voltage droops. When the voltage droop is sufficient to change the number of active modules in the HVPS (which must be an integer when the PWM is disabled) the change from M to $M - 1$ modules is not clean, and the dithering of the number of active modules adds a great deal of noise to the beam and in extreme cases can cause a loss of beam. A klystron amplifier, on the other hand, uses velocity modulation to bunch the beam, and amplification may be controlled by the degree of bunching at constant current, with no voltage droop of the HVPS.

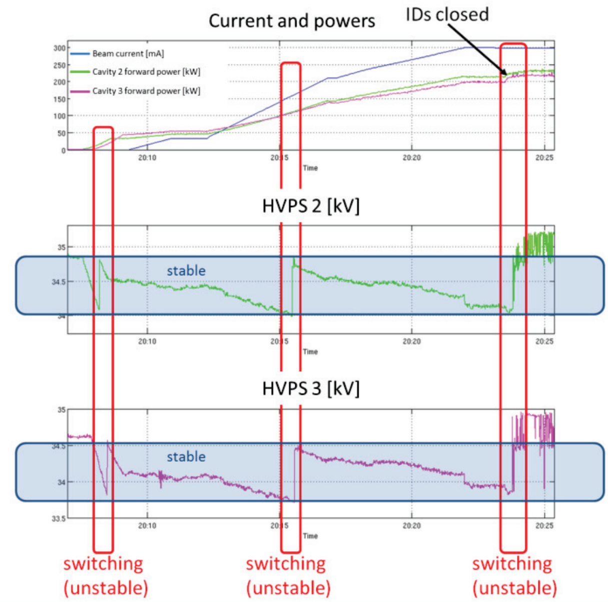

Figure 9: Amplifier power and HVPS voltage during the fill of the storage ring.

The top plot of Figure 9 shows beam current during a 20 minute fill of the storage ring to 300 mA, and the corresponding increase of power from the two amplifiers up to their final values near 230 kW each. The two lower plots illustrate the droop of HVPS voltages in the two operational amplifiers as the power increases and the switching of the modules (ringed in red) that occur when the HVPS has covered the 750 V range corresponding to one module. As long as the voltage demand stays in this 750 V range, highlighted in blue on the figure, the HVPS is stable. The beam can tolerate rapid switching of modules such as that seen during cavity voltage ramp and during beam injection, but if the HVPS demand remains in the switching region for instance at 20:24 in the figure then the HVPS voltage, amplifier output and electron beam in the storage ring all become unstable.

MODIFICATION OF AMPLIFIER CONTROLS

The total power drawn from the two amplifiers supporting the storage ring depends on beam current, which varies slowly during the top-up cycle, and on ID configuration, which is under the control of the users. Also the amplifiers must support non-standard beam currents during machine development shifts and be flexible enough to cope with a reduction in beam current arising from any fault in the injection system. For all of these reasons the 750 V window of stability in the HVPS was considered to be insufficient and so a modification to the HVPS controls was introduced to allow the definition of a user-defined dead-band in the module switching to allow the coverage of all operational configurations.

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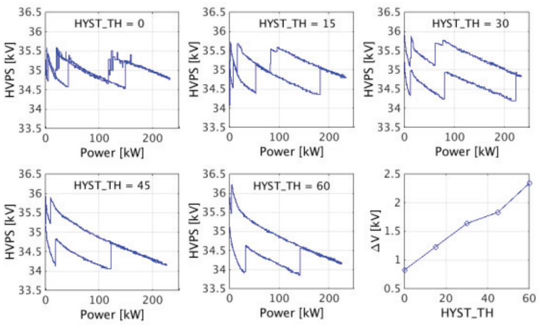

Figure 10: HVPS voltage as a function of output power for different values of *HYST_TH*.

Figure 10 shows the effect of the new parameter *HYST_TH* in defining the dead-band of HVPS switching. The final plot shows the width of the dead-band as a function of *HYST_TH*. An extended test of operation over a start-up weekend demonstrated that values of this parameter above 50 are sufficient to ensure stable operation of the amplifiers.

BEAMLINE MEASUREMENTS

The effects of beam motion on beamline measurements were investigated on B22, Diamond's infrared microspectroscopy beamline [7]. Figure 11 is a comparison of the spectrum of horizontal motion recorded by a BPM with beamline spectra, generated by FTIR spectrometry of a test sample with and without module rotation enabled.

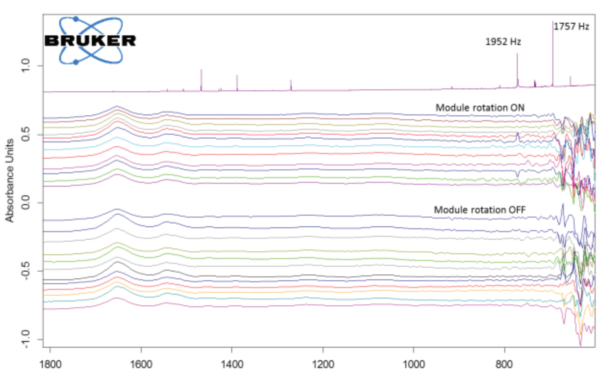

Figure 11: Beam motion spectrum (top) and beamline IR spectra with (middle) and without (bottom) module rotation enabled.

With module rotation enabled the $N = 39$, $M = 64$ line at 1952 Hz can be seen in two of the twelve test spectra acquired with module rotation on but is absent from all of the test spectra taken without module rotation enabled. Many other test spectra were taken during the test with the beamline and in all cases the test spectra were clear of high frequency HVPS module switching features when module rotation was disabled.

Figure 11 also shows that the second order module rotation features from 3500 Hz to 4000 Hz cannot be seen on the intense region of the FTIR spectra from 1300 cm^{-1} to 1500 cm^{-1}, and that there is significant noise on the FTIR spectrum for wavenumbers less than 700 cm^{-1} generated at the beamline which mask any beam-induced spectral features. The existence of this window of sensitivity to module rotation suggests a second approach to the problem of spectral purity, that is the selection of appropriate values of *N* and *M* such that any beam motion induced by the HVPS switching falls in the extremes of signal-to-noise measurement where the beam motion has no effect on the beamline spectrum. Diamond has been operating since May 2015 in this mode for stable values of *N* and *M*, with the sensitive ranges of the FTIR spectra located below the fundamental rotation frequency and between the fundamental and second harmonic of this frequency for the two common modes of operation of the beamline. The parameters *N* and *M* have been chosen such that the jumping of power from peak to peak in the spectrum described above is absent. There have been no reports from the beamline of spectral pollution since the HVPS reconfiguration.

SUMMARY

Sharp lines in the spectrum of the horizontal motion of the beam in the Diamond storage ring have been identified and correlated to the switching of modules in the HVPS of the two high power amplifiers. Fundamental, higher order and intermodulation lines have all been identified on the beam spectrum. These lines may be shifted out of the region of sensitivity of Diamond's IR beamline, or removed entirely by suitable configuration of the HVPS and with a small change to the control system of the module rotation control. Elimination of the lines has been demonstrated on beamline spectra and extended periods of operation have established that the global stability of the storage ring can be maintained even with the modified HVPS.

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