MODEL INDEPENDENT ANALYSIS OF BEAM JITTER ON VELA

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Abstract

The Versatile Electron Linear Accelerator (VELA) is a facility designed to provide high quality electron beams for accelerator systems development, as well as industrial and scientific applications. A key performance indicator for many applications is the inherent beam jitter on the machine (temporal, momentum and positional). Analysis of this beam jitter indicates that there are several independent mechanisms driving the beam motion. We use model independent analysis to correlate various dominant modes of beam jitter and compare them to simulations. We also compare the dominant modes before and after intervention work on the DLLRF timing system, and determine the relevant changes in beam motion.

INTRODUCTION

VELA comprises of a 2.5 cell S-band photocathode gun with copper photocathode providing beam to experiments in the accelerator hall and two dedicated user areas. More information on the layout, design and early commissioning can be found in [1] [2]. The VELA facility ran from April to October 2015 for machine development and as an industrial/academic user facility. During this time significant momentum and transverse beam jitter was reported from both the commissioning team and the users. The momentum jitter was initially assumed to be due to both RF amplitude variations, along with timing variation between the laser and RF system leading to phase jitter as seen by the beam. Analysis of the source of this jitter is complicated by a noticeable laser transverse position jitter seen on the virtual cathode as well as charge jitter recorded by the wall current monitor (WCM). To de-couple the various sources of error, and differentiate the amplitude and timing sources, we used the method of Model Independent Analysis (MIA) [3], equivalent to performing a principle component analysis on the recorded data.

MEASUREMENT SETUP

For analysis of the beam momentum jitter we used 3 beam position monitors, along with a large aperture YAG screen (YAG-04) located in a dispersive region of the beamline and imaged by a digital camera. A WCM signal (WCM-01)was monitored with a high-resolution LeCroy scope. A digital camera based virtual cathode image provided transverse position information for the photo-injector laser (266 nm, ~500 uJ at 10 Hz, ~1 mm FWHM beam diameter). A schematic layout of the beam measurement sources is shown in Fig. 1. The BPM and WCM signals are digitised and distributed via EPICS, whilst the digital camera signals are

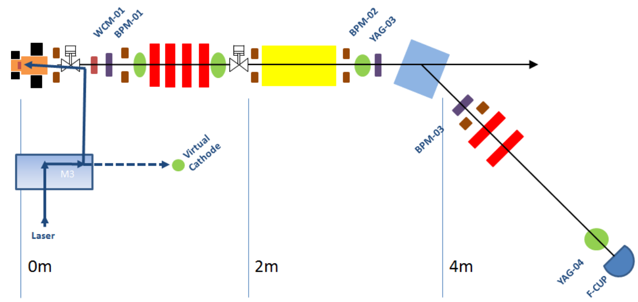

Figure 1: Schematic layout of VELA highlighting relevant diagnostics used in the MIA analysis.

provided via a custom image capture application, with the beam centroid determined from a Gaussian image fitting routine. Due to additional analysis performed in the digitising scope, the BPM and WCM signals are not coincident, with different beam shots recorded at non-coincident EPICS time stamps. Additionally, the camera images are time-stamped according to the local computer system, which are not synchronised to the required accuracy. The time differences between data sources can be determined by noting that the YAG-04 horizontal position should be strongly correlated with the BPM-03 data (since both are at locations of large dispersion). The virtual cathode (VC) and YAG-04 data are correlated due to the induced transverse jitter in the beam, whilst the WCM data is correlated with the VC since the transverse laser jitter samples different quantum efficiencies on the copper cathode surface, leading to variations in bunch charge.

JITTER ANALYSIS

Data was initially recorded in April 2015 using the BPM positions, YAG-04 images and the WCM charge measurements but without the virtual cathode images. The influence of transverse laser jitter could not therefore be confidently determined, although it is expected that the VC position would correlate very strongly with the WCM measurements. Image data from the YAG-04 was recorded in 500 shot bursts at 10 Hz, with a total of 250 s worth of images for each machine setting. In total 4 settings were investigated: gun on-crest with and without dispersion on YAG-04; gun at nominal -20° operating phase with and without dispersion on YAG-04. In all scenarios the decomposition of the instability modes shows correlations relating to horizontal and vertical beam jitter presumably driven by the unseen transverse laser jitter, as well as a dominant eigenmode driven by the energy jitter from the RF/Laser system. In Fig. 2 and Fig. 3 we show the reconstructed beam motion for the on- and off-crest scenarios with finite dispersion at YAG-04. Using the nominal dispersion values at BPM-03 and YAG-04 we determine the

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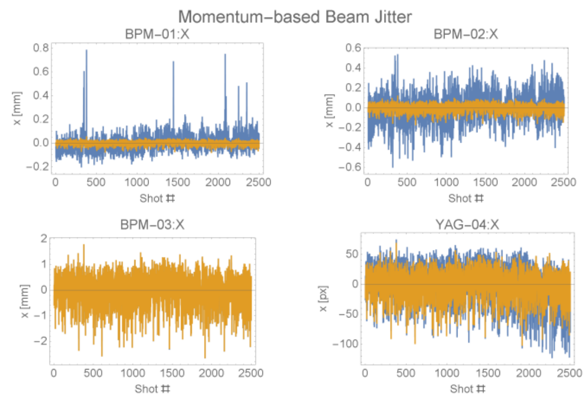

Figure 2: Reconstructed transverse beam motion due to energy jitter at the 4 horizontal monitors at 0° phase.

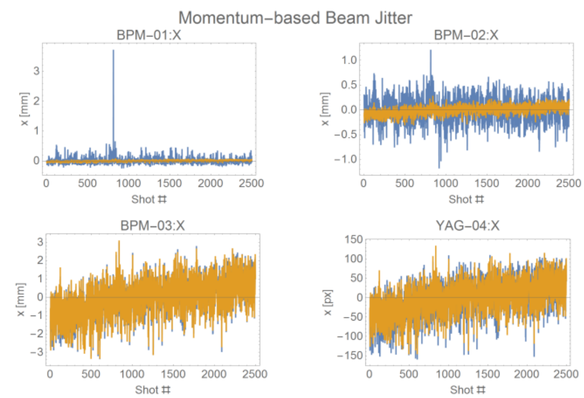

Figure 3: Reconstructed transverse beam motion due to energy jitter at the 4 horizontal monitors at -20° phase.

energy jitter to be (0.132 ± 0.02) % for the on-crest case, and (0.205 ± 0.01) % for the -20° scenario. Assuming that the on-crest jitter is dominated by RF amplitude jitter, with the additional off-crest jitter due to phase jitter, we calculate the amplitude jitter as $\sigma_{amplitude}$ = (0.132±0.02) % with a phase jitter of σ_{phase} = (0.62±0.03)°. To confirm the simple analysis, a more involved simulation of the expected jitter distribution from two independent sources (amplitude and phase errors) was undertaken. The measured distribution of beam positions on BPM-03 was fitted using a combination of two normally distributed error sources. The amplitude variation is assumed to come from the klystron, which has been shown to vary sinusoidally with time [4], and we assume normally distributed jitter on top of this sine curve. The phase variation is assumed to be due to variation in the laser-RF timing, and is normally distributed, with the energy jitter given by the non-symmetric phase curve for the 2.5-cell gun. Using Probability Density Functions of the fitted and simulated data we find that the modelled amplitude jitter is (0.12±0.02) % with a phase jitter of (0.57±0.06)°.

MEASUREMENTS TO DISCOVER THE SOURCE OF DRIFT

Figure 3 shows a slow drift in momentum for the two dispersive monitors, equating to a drift in the crest-phase of -5.38°/hr. The RF Master Oscillator (MO) produces two synchronised signals at 81.04 MHz and 2998.5 MHz. An additional diagnostic signal is provided by the use of an Analog Devices AD9914 direct digital synthesiser (DDS) evaluation board. The system was then measured against the photo-injector laser signal at 81 MHz via standard photo-diode(1 ns rise time). Using two Analog Devices 8302 phase detection circuits, the relative phase between the RF 81 MHz (A) digitally divided DDS 81 MHz (B) signal, along with the 81 MHz laser signal (C) were measured over a period of 8 hours using the setup shown in Fig. 4. The resulting

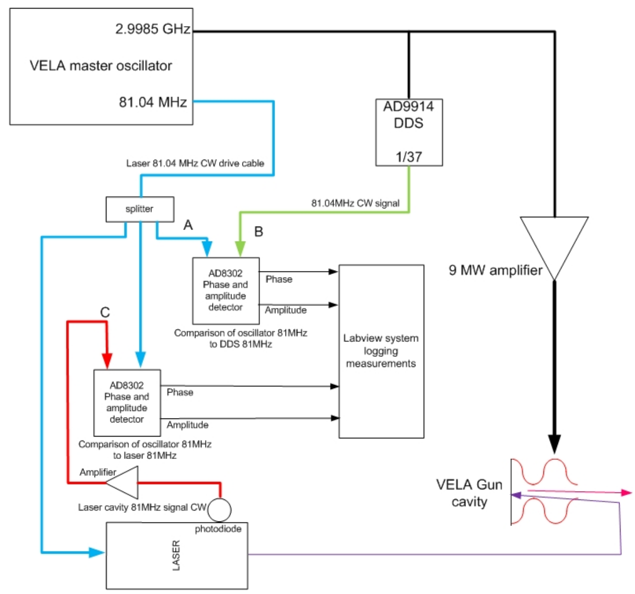

Figure 4: Layout of the MO phase measurement circuit.

analysis, shown in Fig. 5, indicates a constant drift between the 81 MHz RF signal and the digitally-divided 81.04 MHz RF signal, with a gradient of 0.1°/hr at 81.04 MHz, equivalent to -3.7°/h at 2998.5 MHz. Drift between the RF and laser signals showed a sinusoidal variation, indicative of temperature effects. The MO analysed used a 100 MHz

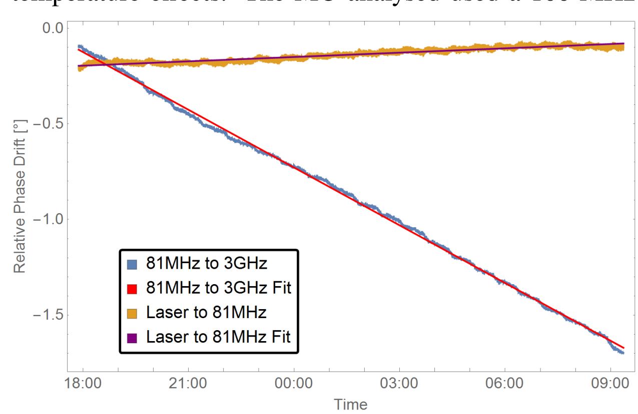

Figure 5: Measured relative phase variation between the RF 81 MHz and 3 GHz signals, and the 81 MHz and Laser signals.

Oven Controlled Crystal Oscillator (OCXO) as a reference, with 900 MHz signals generated using frequency multipliers. The 2998.5 MHz upper frequency and the lower frequency of 1/37th of upper value (81.0405 MHz) are derived separately: the upper frequency is generated by a combination

ISBN 978-3-95450-147-2

of mixer operations and multipliers; the lower frequency is generated using Direct Digital Synthesis (DDS) as part of the circuit shown in Fig. 6. The DDS cannot represent exactly the required frequency since this necessitates an integer Frequency Tuning Word (FTW), whereas the required ratio is 53 366 134 097 979.779 $\overline{459}$ [5]. Assuming the number is rounded up, the resulting error in the frequency is 0.705 µHz. This affects f_{81} to the order of 0.07835 µHz, equating to a phase change of 0.101°/h. This implies that, while the digitally divided 81 MHz signal was maintaining phase lock with the 3 GHz signal, the 81 MHz master oscillator signal was in fact constantly slipping in phase. The use of the AD9914 in this test is significant in two ways: the device can be directly clocked at up to 3.5GHz; and it can be used in variable modulus mode where its division ratio need not be an integer of two. This enabled the DDS to be clocked at 2998.5MHz and produce an exact divided output of 1/37 = 81.04MHz. To remove the phase drift in the MO, the AD9914 DDS 81.04 MHz was therefore used to drive the laser system and the machine was tested again. Subsequent phase noise measurement analysis of the AD9914 DDS using a Holzworth Instruments HA7062B phase noise analyser found that its output phase noise profile was extremely good and comparable with the original oscillator.

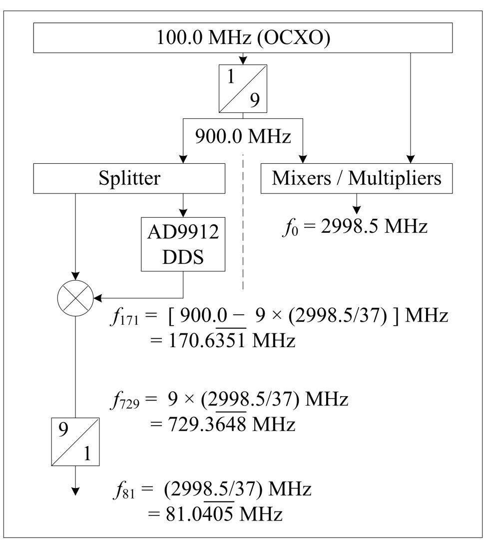

Figure 6: Initial frequency multiplexing circuit using AD9912 DDS.

JITTER ANALYSIS: WITH DDS

After installation of the DDS and phase locking electronics, a similar analysis of the beam jitter was performed to that in April. Improvements to the various monitoring systems enabled correlations between the BPMs, YAG-04, WCM and Virtual Cathode to be recorded simultaneously. Introduction of the VC position highlighted a very strong eigenmode related to transverse laser motion, which is expected to be significantly reduced in future runs with the introduction of a commercial feedback system [6]. Reconstruction of the beam momentum jitter in the on-crest case was straightforward, and revealed a momentum jitter of (0.16±0.04) % on both BPM-03 and YAG-04. Analysis of the recorded data in the off-crest regime indicated at least two eigenmodes that appeared to be driven by momentum jitter. The combined jitter from both modes is equal to (0.16±0.02) %, in line with the on-crest momentum jitter. The two modes show individual jitter amplitudes of 0.13 % and 0.08 % respectively. We make the assumption that the larger amplitude eigenmode is due to RF amplitude jitter, with the smaller eigenmode due to phase jitter. This gives a reduced phase jitter of (0.43±0.05)°. Simulations of the jitter distributions in the on-crest and the combined off-crest reconstructions give an amplitude jitter of (0.15±0.02) % and a phase jitter of (0.45±0.07)°, in line with the simple analysis. Fig. 7 shows the distributions and their fitted probability density functions for the on- and off-crest scenarios.

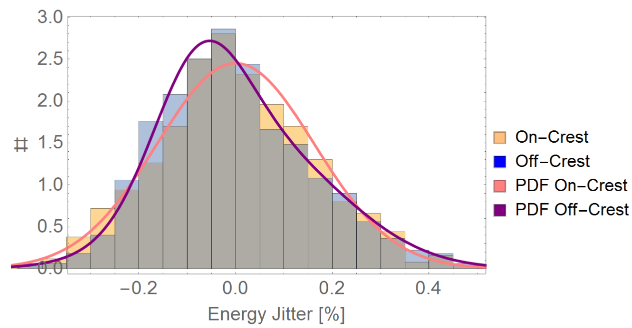

Figure 7: Distributions and estimated Probability Density Functions for the reconstructed On- and Off-crest jitter data.

CONCLUSION

Analysis of the beam jitter on VELA has been measured and analysed using the principles of Model Independent Analysis. The measurements showed a significant momentum jitter arising from both timing jitter between the laser and RF systems, as well as amplitude jitter driven by the RF modulator. Additional measurements of the RF MO system, showed a long term drift between the 81 MHz and 3 GHz signals, which was ultimately corrected by installation of a DDS based MO system. Measurements of the momentum jitter with the DDS installed show an small increase in the amplitude jitter, but a noticeable reduction in the phase jitter as seen by the beam. The eigenmode reconstruction also highlighted a large component driven by transverse laser position jitter, which should be improved by the subsequent introduction of a commercial feedback system operating on the laser pointing stability.

ACKNOWLEDGEMENT

The authors would like to acknowledge the guidance and advice of our former colleague Alexander Kalinin who was supportive of the trials of DDS technology. We would also like to thank Colin Horrabin (G3SBI) and Martein Bakker (PA3AKE) and the group at Analog Devices Inc, for their help with the final implementation of the DDS-based RF timing system.

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ISBN 978-3-95450-147-2