# A Low Phase Noise 1.3 GHz Dielectric Resonator Oscillator

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***Abstract*— A low cost, low phase noise 1.3 GHz Dielectric Resonator Oscillator (DRO) has been developed to synchronise and drive cryogenic cavity resonators used in particle accelerators. The oscillator is based on a simple loop oscillator design. The resonator is temperature controlled to improve the temperature stability. The phase noise has been measured at -121dBc/Hz at 1kHz and reaches the thermal limit far from the carrier. The vibration sensitivity has been measured to be better than $10^{-7}$.**

## I. INTRODUCTION

Voltage Controlled Oscillators with good phase noise at offsets both close to, and far from, the carrier are useful as clean-up fly-wheel oscillators in systems which require highly precise, low jitter timing. Such systems include linear accelerators similar to those being built for the Free Electron Laser at DESY in Hamburg or the National Linear Accelerator in Chicago. In these systems a highly precise signal derived from an atomic reference or maser is distributed to remote locations using fibre optic links. However, those links are not able to distribute signals with low enough jitter (integrated phase noise) to meet the stringent requirements needed in those systems.

This paper describes flywheel oscillators which can be synchronised to the reference oscillator via the fibre link, but which have phase noise performance both close to and far from the carrier, which is low enough to clean up the jitter introduced by the fibre links, and thereby achieve the very stringent jitter requirements of these systems.

A Dielectric Resonator Oscillator architecture was selected so as to provide high Q factor and high power handling ability, so that both close to, and far from carrier, noise requirements could be met.

## II. DESIGN

The 1.3 GHz DRO is designed as a loop oscillator comprising of the dielectric resonator, loop amplifier, varactor phase shifter and an output coupler. Fig 1 shows a block diagram of the loop oscillator configuration. It can be seen that the RF power output is taken after the dielectric resonator. This results in the far from carrier phase noise reaching the thermal limit, as the resonator is used to filter the loop amplifier noise outside of the cavity bandwidth. This does decrease the available RF output power of the DRO by the insertion loss of the resonator, however for this application far from carrier phase noise performance was a more significant requirement.

For the loop shown in Fig 1 to oscillate two conditions need to be met: i) The phase around the loop needs to be a multiple of $2\pi$; and ii) the loop gain needs to be greater than 0dB (before compression). For loop oscillators we prefer to couple the resonator such that the insertion loss of the resonator is 9dB. A 10dB coupler was used to couple power back around the loop. Loss through the output coupler and connectors is estimated to be 1dB. Output power from the DRO was required to be 13dBm demanding that the loop amplifier has at least 23dBm output power. We used two amplifiers in series to provide us with 24dBm output power and 28dB gain. With 28 dB gain we were able to achieve a maximum gain margin around the loop of 7dB. A fixed attenuator (not shown in Fig 1) was designed into the loop to lower the gain margin to about 5dB.

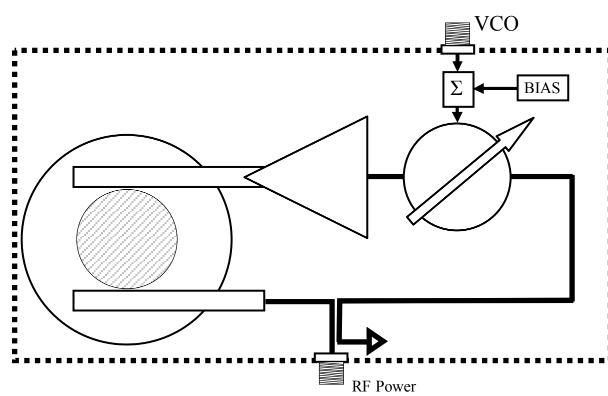


Figure 1. Block diagram of Dielectric Resonator Oscillator

The phase noise of the DRO was modeled using a method described by Tanski (1). The amplifiers chosen to be used in the design have been used in other PSI products and we have measured residual noise of -130dBc/Hz at 1Hz. With the required phase noise performance of the DRO known we were able to calculate the loaded Q required from the resonator. This was calculated to be 13,000.

With the coupling to the resonator set to give an insertion loss of 9dB the unloaded Q of the resonator can be calculated to be about 21,000. This was achieved using a standard "off the shelf" dielectric puck and a relatively small cavity. It is known that to achieve the maximum unloaded Q from a dielectric puck, the walls of the cavity needs to be distanced far enough away from the puck so as to have minimal interference with the electric field. As a general rule the cavity inside diameter should be about 3 times the diameter of the dielectric puck. As the cavity diameter is decreased, the walls of the cavity interfere with the electric field and the Q is degraded. We were able to achieve the required unloaded Q of the resonator with a cavity diameter only 1.7 times larger than the dielectric puck diameter. Although the unloaded Q of the resonator is compromised, the resulting cavity is much smaller and lighter.

The resonator was designed to have minimal amount of mechanical tuning, to minimize any external vibration being injected onto the oscillator spectrum through the mechanical tuning disc. It was decided that 400kHz (300ppm) of tuning would allow for aging in the puck. As we had limited mechanical tuning in the resonator frequency, the dielectric pucks needed to be modified to set their centre frequency within range of the mechanical tuning. Fig 2 shows the centre frequency of each of the pucks with the mechanical tuning set to mid range. The shaded band shows the amount of tuning available from the mechanical tuning. Each dielectric puck was "machined" by using 200grit sandpaper on a flat surface and reducing the thickness of the dielectric puck. The two pucks above the mechanical tuning band were set on a higher spacer to reduce their resonate frequency.

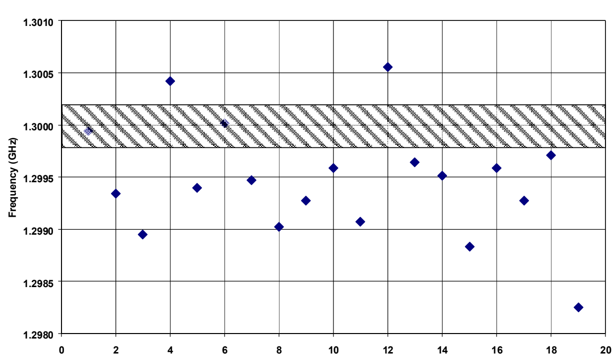


Figure 2. Dielectric puck centre frequency before tuning

## III. PHASE NOISE

The final phase noise of two DRO's, measured on an ODIN 320A, is shown in Fig 3. A cross spectrum phase noise measurement technique is used. It is assumed each oscillator is similar in phase noise and therefore 3dB can be subtracted from the measurement for a single oscillator measurement.

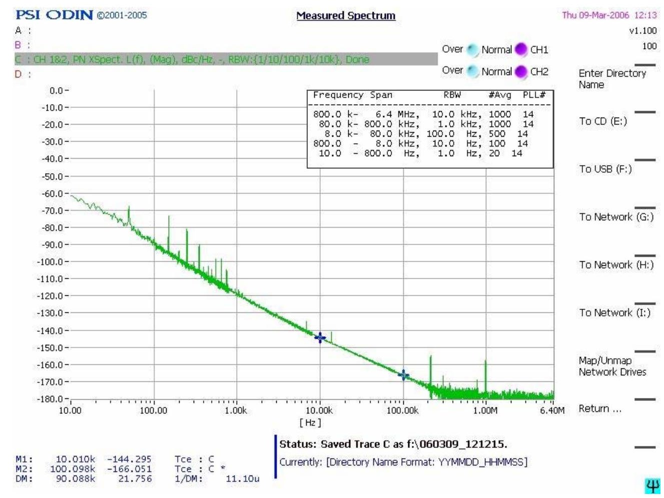


Figure 3. Measured phase noise using ODIN 320A

Fig 4 shows the modeled noise against the measured phase noise. The measured phase noise is the same data shown in Fig 3, however 3dB has been subtracted for the single oscillator measurement. The measured phase noise did not meet the modeled noise, and degradation from the ideal $1/f^3$ noise is seen in the measurement around 10kHz. Investigation found that the loop amplifier used in the DRO had increased noise as it was driven into compression.

The modeled phase noise assumed a non- filtered port output. It can be seen from Fig 4 the effect of the filtering of the cavity to improve the far from carrier phase noise.

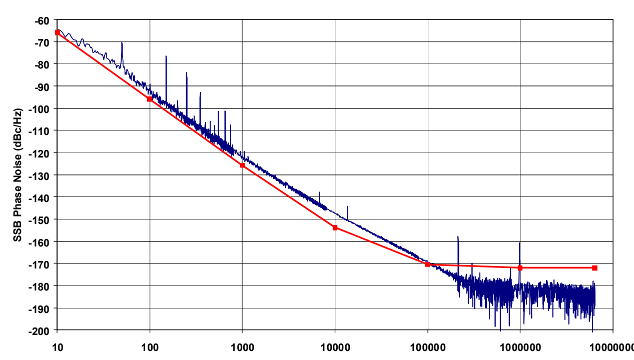


Figure 4. Predicted and measured phase noise.

The gain margin of the oscillator was designed to be 5dB. Reducing the gain margin, and thereby reducing the incident power on the loop amplifier showed the phase noise performance of the oscillator improved as the gain margin was decreased. Fig 5 shows the same two oscillators with the gain margin decreasing in both. It can be seen that the phase noise improves dramatically for only a 2dB difference in gain margin. It was decided to run the oscillator under 3dB of gain margin as it was able to meet our phase noise requirement but still provided a comfortable level of gain margin. It should be noted that around 100kHz the phase noise measurement is limited by a single channel phase noise measurement in Fig 5.

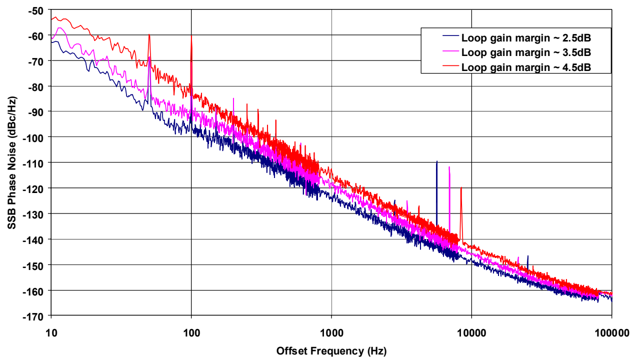


Figure 5. Phase noise with varying loop gain margin

The large effect of gain margin on the amplifier noise is not yet understood and further investigation is required to identify the problem and to redesign the circuit to eliminate the problem.

## IV. TEMPERATURE CONTROL

Loboda (2) describes two effects when characterising the temperature sensitivity of a DRO. These are referred to the dynamic temperature sensitivity and the static temperature sensitivity.

The dynamic temperature sensitivity is a function of the rate of change of ambient temperature. The most likely reason for the dynamic temperature sensitivity is that the copper cavity can respond quickly to ambient temperature variation. The thermal expansion of the copper means it will expand and contract at a much quicker rate than the dielectric puck, which is in poor thermal contact with ambient temperature, mainly due to the poor thermal conductivity of the stand off on which the dielectric puck is mounted. Only after a length of time does the dielectric puck and the cavity come into equilibrium.

Once the cavity and the dielectric puck are in equilibrium, the difference in frequency between the initial ambient temperature and the final ambient temperature is referred to the static temperature sensitivity. The static temperature sensitivity is a function of the temperature coefficient of the dielectric constant, thermal expansion of the dielectric material and the thermal expansion of the cavity.

It is assumed that any differences in the differential expansion between the cavity material and the dielectric puck material will contribute to the static temperature dependence of the resonator.

To reduce the temperature sensitivity of the DRO a simple proportional temperature control circuit is used to heat the resonator. A resistive heater mat is wrapped around the copper cavity and a NTC thermistor is used to sense the temperature. The ambient temperature operating range of the DRO is 10°C to 30°C (50°F to 86°F) The temperature control is designed to heat the cavity to around 35°C (95°F). A polystyrene insulator covers the heater mat and a stainless steel cover is put over the polystyrene insulator. G10 which has poor thermal conductivity is used for the base of the DRO. This arrangement is used as it insulates the DRO from ambient temperature, reducing the power required to keep the DRO at the elevated temperature. It also helps reduce any ambient temperature fluctuations on the cavity minimising the dynamic temperature sensitivity.

To test the temperature control circuit the DRO was placed in a temperature chamber and the ambient temperature varied over the operating range of the DRO. The ambient temperature is started at 10°C and is ramped up to 30°C at a rate of 1°C/minute. The DRO is kept at 30°C until it has come into equilibrium and the frequency has settled. The ambient temperature is then reduced to 10°C again at a rate of 1°C/minute and kept at 10°C until the frequency has settled. This process is repeated, this time the rate of change of the ambient temperature is increased to 5°C/minute.

Fig 6 shows a DRO run over the temperature profile described above with the temperature control disabled and then with the temperature control enabled. It should be noted that with the temperature control disabled, the DRO still had the cavity insulated from the ambient temperature with the polystyrene foam, stainless steel cover and the poor thermal conductivity base plate still in place.

The most obvious difference between the temperature control enabled and disabled is the reduced dynamic temperature sensitivity. The frequency excursion due to the dynamic temperature sensitivity has been reduced from around 20kHz to only a few hundred hertz.

Interestingly with the with the temperature control enabled the static temperature coefficient is worse. With the temperature control disabled the static temperature sensitivity is 0.11ppm/°C while with the temperature control enabled the static temperature sensitivity is 0.15ppm/°C. This can be explained because the thermal expansion of the cavity and the dielectric puck is well matched. With the temperature control disabled the cavity and dielectric puck can come into equilibrium and then the ratio of the diameters is constant.

When the temperature control is enabled, the cavity and the puck will have small temperatures differences as the ambient temperature is varied. This arises due to thermal gradients between the copper cavity walls which are being heated and the dielectric puck.

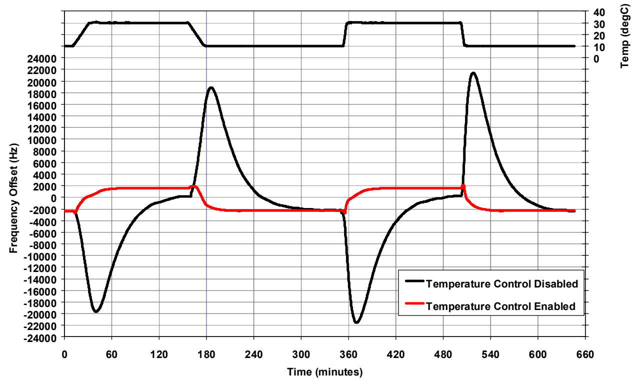


Figure 6. Temperature sensitivity of a DRO with the temperature control enabled and disabled

## V. VCO TUNING CHARACTERISTICS

Fig 7 below shows the frequency and RF output power response as a function of the VCO input voltage. The VCO has been tuned to provide 2kHz/V tuning around 0V. This is required as the DRO will be phased locked to a reference and the PLL gain and therefore bandwidth is a function of the VCO tuning slope. It may be necessary to limit the VCO tuning range for the DRO as at the positive extreme the loop gain margin of the oscillator is marginal at only around 1dB.

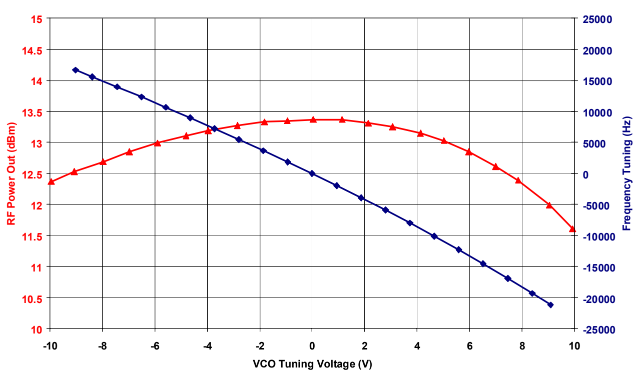


Figure 7. RF Power and frequency tuning of DRO

## VI. VIBRATION SENSITIVITY

The DRO vibration sensitivity was measured by placing the DRO on a vibration table and phase locking it to a second DRO and measuring the phase noise. The vibration table is limited to discrete tones. The DRO mounted on the vibration table was subjected to a discrete tone and the amplitude of the vibration measured using an accelerometer. The resulting degradation in phase noise was measured at the induced tone frequency and the resulting vibration sensitivity can be calculated using the equation below.

$$\Gamma_i = \frac{2 f_v}{a_i f_o} 10^{\left(\frac{\mathscr{L}(f_v)}{20}\right)}$$

where $a_i$ is now represented in $g$'s peak, $f_v$ is the frequency of the vibration tone, $f_o$ is the carrier frequency, and $\mathscr{L}(f_v)$ is the magnitude of the rms phase tone measured from the SSB phase noise plot (normalised to a 1Hz bandwidth).

The DRO was subjected to the discrete tones in each of the 3 axis. Fig 8 below shows the result of the vibration

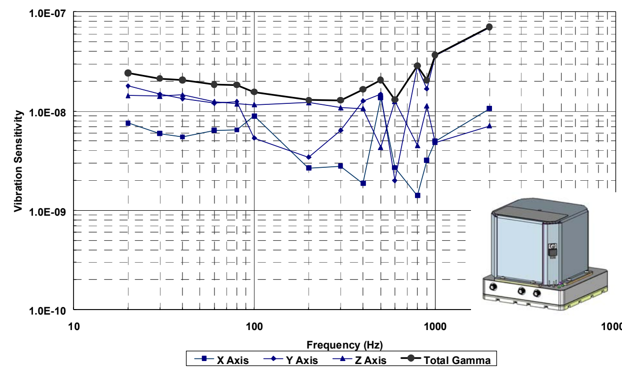


Figure 8. 3axis vibration sensitivity of DRO

## VII. CONCLUSION

A low cost 1.3GHz DRO based on a filtered port loop architecture has been designed providing phase noise performance of -121dBc/Hz at 1kHz offset and reaching the thermal limit at far from carrier offsets. The amplifier has been found to be limiting the phase noise of the oscillator and work will be done to improve the design to reduce the phase noise of the oscillator. The temperature stabilized resonator has been shown to greatly reduce the dynamic temperature sensitivity of the oscillator allowing the DRO to be used in environments where rapid temperature variations may exist. The vibration sensitivity of the DRO has been measured and found to be better than $10^{-7}$

## REFERENCES


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[3] MJ Loboda, TE Parker, GK Montress, "Temperature Sensitivity Of Dielectric Resonators and Dielectric Resonaotr Oscillators" Proceedings of the 1988 42nd Annual Frequency Control Symposium pp263-271