

Basic PICmicro[®] Oscillator Design

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INTRODUCTION

The oscillator circuit for almost any microcontroller is a fairly simple design with very few components. Selecting the values for capacitors and resistors from the manufacturers' data books will get you a circuit that oscillates. However, many conditions can adversely affect the performance of your oscillator design. Higher temperatures and lower supply voltages can lower the amplifier gain (and thus the loop gain in the oscillator circuit) causing poor, slow, or no start-up. Colder temperatures and higher supply voltages can increase amplifier gain, causing the circuit to be forced to a higher harmonic and throw off the timing. The crystal can also be overdriven and become potentially damaged and cease functioning altogether. It is also possible to waste power through the improper selection of components or Clock modes.

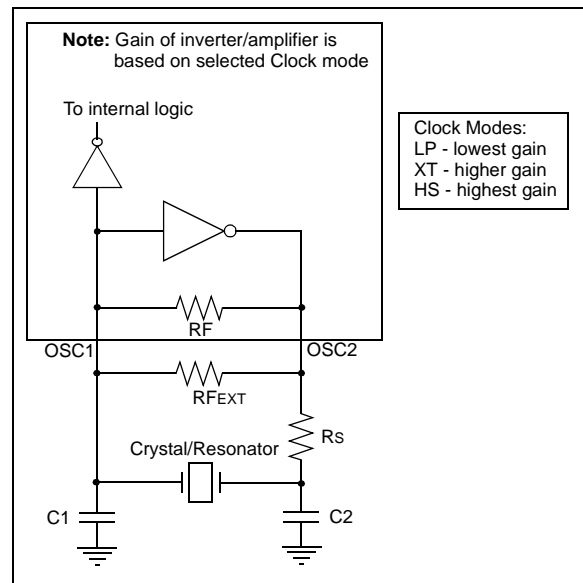
The purpose of this Application Note is to provide a fundamental explanation for the functioning of the oscillator circuit, and to demonstrate some methods for assuring your design is sound. It is not intended to supersede the data sheet in any way and is offered as design assistance to help the designer understand and verify their oscillator circuit. We will start with a discussion on the oscillator circuit itself, proceed to a description of the function and characteristics of each component, offer several methods of improving and verifying your design, and conclude with a series of lab experiments which demonstrate the issues discussed here. The goal is to help you achieve a fail-proof final design that oscillates over the range of temperature and voltage you expect your circuit to experience, without damaging components and leaving as much margin for error as possible to overcome variations in board manufacturing and silicon processes.

Most of the time using the values given in the manufacturers' data book tables will work fine. Microchip microcontrollers are able to run with clocks from 0.0 MHz to over 40 MHz, supply voltages from 2.0 V_{DC} to 6.25 V_{DC} and temperatures from -40 degrees C to 125 degrees C, depending on the part and version ordered. All this must be done with crystals or resonators of varying quality and manufacture. This creates many chances for exceptions to the values given in the data book.

The Oscillator Circuit

The circuit shown in Figure 1 is a typical parallel resonant oscillator circuit, as used with the Microchip PICmicro family of devices. The output of an inverting amplifier is fed back to its input to create an "unstable" loop. When the inverter output is high and is fed back to the input, this causes the output to go low, which reverses the process. Stable oscillation is achieved when the output is delayed by enough to provide 360 degrees of delay in the circuit and the circuit components attached achieve this feedback with "unity gain" only at the desired frequency. Frequencies other than the desired frequency are filtered by the oscillator circuit and are, therefore, not amplified back into the signal. Oscillation is achieved when the signal rings back and forth through the crystal or resonator, sustained by the energy stored in the capacitors.

FIGURE 1: PARALLEL RESONANT OSCILLATOR CIRCUIT



THE PURPOSE OF COMPONENTS AND CLOCK MODES

A good place to begin is with the purpose of each circuit component. Because this is a loop circuit, a change in one component can change the effect of other components in the circuit. Therefore, a definition of purpose is a simplification for clarity only.

Inverting Amplifier

The Inverting Amplifier is the workhorse of the circuit. It must provide enough gain to amplify a very small signal at start-up where only noise is provided to the input. The desired signal is achieved only after the amplified noise has been filtered by the external oscillator circuit and fed back to the input, where it is further amplified. The amplifier amplifies all signals arbitrarily, so little filtering occurs there. Fortunately, crystals and resonators provide a band-pass function with very sharp cut-off. This helps assure that only the resonant crystal frequencies are permitted a path back to the amplifier input, where they are added back into the signal to make their way once more to the input, to be amplified yet again. If the desired signal is increased each time until a stable oscillating signal is achieved, the circuit is said to have Unity Gain at that frequency. In other words, there is enough gain for that signal to be sustained indefinitely. If the amplifier has much more gain than necessary, then undesired noise still has a chance of getting enough amplification to stay in the signal. If there is not enough gain, then the desired signal is at risk of being lost and the oscillator can die out or, more likely, never start-up.

Because crystals and resonators have more than one resonant frequency, part of the circuit designer's job is to design the oscillator circuit such that undesired harmonics are not amplified enough to sustain oscillation.

Oscillation is achieved when a charge bounces back and forth through the crystal or resonator, between the capacitors. The amplifier is then adding a push at the right time and of the right amount to sustain oscillation. This principal is very similar to the kind of push that keeps a pendulum swinging or a ball bouncing. If timed correctly (phase delay), and given the right amount of energy (gain), very little power is needed to sustain the oscillation. Therefore, the oscillator circuit can also be an important place to fine-tune performance to save power. Crystals and resonators are so good at filtering frequencies outside of the rated fundamental frequency that the designer is mostly concerned with assuring that:

- the desired frequency is sustained
- the circuit can start-up properly
- energy is not wasted
- noise is not unnecessarily amplified

Most of the discussion for this Application Note centers on understanding, achieving, and testing this ideal design.

Clock Mode

The Clock mode is the programmable gain of the inverting amplifier (except RC or EC mode, which uses a RC network to determine oscillation frequency). The lower Frequency modes have lower gain and the gain increases for higher Frequency modes. For instance, in the PIC16 family, the Clock mode gain from lowest to highest is:

- LP (Low Power, or lowest gain)
- XT (standard Crystal mode, moderate gain)
- HS (High Speed, or highest gain).

More energy is required to sustain higher frequency oscillation and therefore, the higher Gain modes provide the energy needed for higher speed operation while lower Gain modes reduce wasted power, overdrive and noise when running at lower frequencies.

The Microchip data book provides tables to guide in the selection of Clock modes. One such table is shown in Table 1.

TABLE 1: CAPACITOR SELECTION FOR CRYSTAL OSCILLATOR

Osc Type	Crystal Freq.	Cap. Range C1	Cap. Range C2
LP	32 kHz	33 pF	33 pF
	200 kHz	15 pF	15 pF
XT	200 kHz	47-68 pF	47-68 pF
	1 MHz	15 pF	15 pF
	4 MHz	15 pF	15 pF
HS	4 MHz	15 pF	15 pF
	8 MHz	15-33 pF	15-33 pF
	20 MHz	15-33 pF	15-33 pF
Note: These values are for design guidance only.			
Crystals Used			
32 kHz	Epson C-001R32.768K-A	±20 PPM	
200 kHz	STD XTL 200.000KHz	±20 PPM	
1 MHz	ECS ECS-10-13-1	±50 PPM	
4 MHz	ECS ECS-40-20-1	±50 PPM	
8 MHz	EPSON CA-301 8.000M-C	±30 PPM	
20 MHz	EPSON CA-301 20.000M-C	±30 PPM	

It is possible to select a higher or lower gain than specified by the data book if desired, based on the specific needs of the oscillator circuit. In circuits where low power consumption is critical, a lower gain Clock mode can help. Conversely, if the circuit is running at a low voltage or high temperatures, a higher gain may be desirable. Unnecessarily overdriving crystals is to be avoided. There are potential trade-offs for selecting a higher or lower Gain mode than needed. A higher Gain mode may improve start-up, but waste energy or overdrive a crystal. A lower Gain mode may save energy and reduce stress on the crystal, but fail to start-up under certain conditions. (These topics are discussed in detail later).

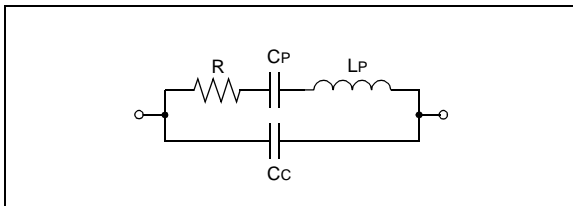
The Crystal

The Crystal has its lowest AC impedance near the resonant frequency. The crystal is placed in the path between the output and input of the inverting amplifier to permit feedback and therefore oscillation at the desired resonant frequency.

Crystal and Resonator Equivalent Circuit

Figure 2 illustrates an equivalent circuit for a crystal or resonator.

FIGURE 2: CRYSTAL AND RESONATOR EQUIVALENT CIRCUIT



C_C represents the case capacitance across the crystal or resonator terminals; R , C_P and L_P are known as the motional arm of the crystal or resonator. In parallel Resonant mode (i.e., anti-resonance), the crystal or resonator will look inductive to the circuit. At the resonant frequency, the crystal or resonator will look and perform like a low resistance.

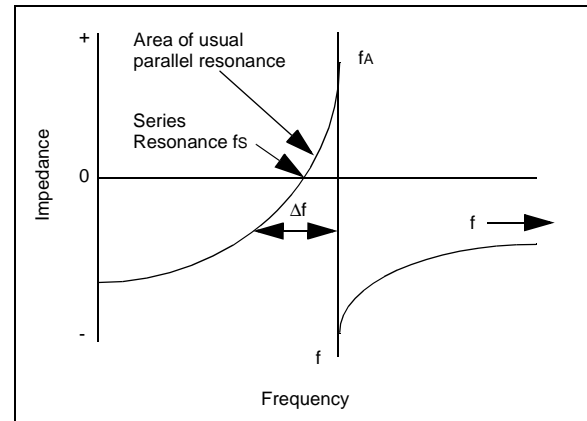
Impedance Curve of a Typical Crystal

The next diagram (Figure 3) illustrates the impedance/reactance vs. frequency of the crystal. Impedance is at a minimum at the series resonant frequency F_s . Impedance reaches its peak at f_A , which is technically the parallel Resonance mode. In practice, even a parallel resonant circuit actually operates near the series resonant frequency, with a load capacitance specified by the crystal or resonator manufacturer that assures oscillation at the rated frequency when used in a paral-

lel resonant circuit. The load capacitance should be selected to operate the crystal at a stable point on the f_s - f_A reactive curve (as close to f_s as possible).

Note: Even parallel resonant crystals have a series resonant frequency, f_s .

FIGURE 3: IMPEDANCE/REACTANCE VS CRYSTAL FREQUENCY



Crystals are usually selected by their parallel resonant frequency only; however, other parameters may be important to your design such as temperature or frequency tolerance. Microchip Application Note AN588 is a good reference if you would like to know more about crystal operation and their ordering information. Most crystal and resonator manufacturers provide detailed descriptions of the various parameters, which can be defined when ordering crystals and resonators.

Purpose of Capacitors

The capacitors C_1 and C_2 make up the rest of the basic oscillator circuit when combined with the inverting amplifier and the crystal or resonator. Again, when the circuit is ringing at the resonant frequency, charge is transferred back and forth through the crystal or resonator, between the capacitors. Both capacitors, then, work together to sustain the oscillation. Generally, they are chosen to be the same value to provide a symmetrical store of energy on both sides of the crystal or resonator and are chosen to match the load capacitance specified by the crystal or resonator manufacturer. The capacitors provide 90 degrees of the phase shift, 45 degrees for each capacitor, with the crystal or resonator providing 90 degrees of the phase shift (seen as a resistive element at resonant frequency) with the inverting amplifier providing the final 180 degrees to achieve the total 360 degrees required by the circuit.

Crystal manufacturers typically rate their crystals to operate closest to the specified frequency if they have a load capacitance of 20 pF to 30 pF. C1 and C2 are typically between 10 pF and 50 pF (sometimes more for resonators, discussed later). Values of capacitors higher than 33 pF and the power they waste, can often be avoided by adding a series resistor R_s , discussed momentarily. Values lower than 10 pF are avoided since the capacitors also perform the secondary function of decoupling stray noise from the oscillator signal, which could become part of the signal and perhaps even cause spurious clocking internally, affecting the program execution timing.

Load capacitance should be selected, at least to start with, per the data supplied by the crystal or resonator manufacturer for a parallel resonant circuit. The capacitors are seen as being in series by the oscillating circuit, in terms of their load, and therefore the equation is a simple formula for series capacitors. This will assure that the circuit oscillates at the rated frequency. Load capacitance can be calculated using the formula shown in Equation 1:

EQUATION 1: LOAD CAPACITANCE FORMULA

$$\frac{C1 \times C2}{C1 + C2} + C_{stray}$$

C_{stray} in the above equation can be:

- pin capacitance
- capacitor, resistor, and crystal or resonator lead capacitance
- board or trace related capacitance.

In total, this is often in the range of 5-15 pF. If the Microchip data book shows 15 pF capacitors for C1 and C2, and your board and device have about 12.5 pF C_{stray} , then the resulting load capacitance in pF is $[(15 \times 15) / (15 + 15)] + 12.5 = 20$ pF. If the crystal manufacturer suggests a 20 pF load capacitance, this is an excellent place to start. If you were to increase C2 to 33 pF (to decrease gain, discussed below), the resulting load capacitance is still 22.8 pF. In most cases small deviations like this will not "pull" the resulting resonant frequency appreciably; however, larger changes could very well alter the resulting oscillator frequency. If very tight frequency accuracy is important, stay as close to the rated load capacitance as possible.

Even though the capacitors form a symmetrical circuit with the crystal or oscillator, there are differences in how they affect the circuit, and these differences can be used to your advantage when tuning the circuit.

Ideally, the lowest capacitance is chosen (within the range of the recommended crystal load) that will oscillate in the lowest appropriate Gain mode, at the highest temperature (and lowest V_{DD}) under which the circuit will be expected to perform. High temperature and low

V_{DD} both have a limiting affect on the amplifier gain such that if the circuit functions at these lower gain extremes the designer can be assured of proper start-up and operation at other temperatures and supply voltages. Another method for improving start-up is to use a value where one of the capacitors is larger than the other. Usually this is done by making C2 greater than C1. This can cause a greater phase shift across the crystal at power-up, which can speed oscillator start-up. Once the start-up is assured, overdrive is limited with R_s if needed, which will be explained shortly.

Measuring Power

Capacitor values that are too high can store and dump too much current through the crystal, so for this reason C1 and C2 should not become excessively large. Unfortunately, measuring the wattage through a crystal can be tricky business, requiring a sensitive current probe able to deal with the high frequency and sufficient room on the board to mount the probe.

You can temporarily disconnect one lead of the crystal or resonator and place a series resistor in series with it. The resistor should be of the same value as the crystal impedance at resonance (taken from the crystal data sheet). Measure the voltage across this R_T (temporary test resistor) and compute the RMS current and power. Resonator ESR (Equivalent Series Resistance) is typically between 20 and 150 ohms. Crystal ESR is typically between 20 and 1000 ohms at the resonant frequency.

The resulting waveform is not always entirely symmetrical since it will be loaded by the measuring device, and so may not be easy to convert to an accurate measurement. One nice thing about this test is that it makes it more evident when a crystal is being overdriven. Figure 4 is a scope snapshot depicting the waveform across a resistor directly in series with the crystal (not connected as R_s , between the output pin and the capacitor) in a circuit where the crystal is being overdriven at over 50 mW; hence, the severe clipping. Typical maximum wattage for a crystal is between 1 and 2 mW.

Figure 5 is a scope snapshot taken in the same circuit once the drive condition was reduced to 1.25 mW. Both diagrams were created by connecting two scope probes, one at either end of the series resistor in test, then subtracting one waveform from the other using a storage scope. Fortunately, if you do not stray too far from the suggested values, you should not have to be concerned with this.

FIGURE 4: OVERDRIVEN CRYSTAL

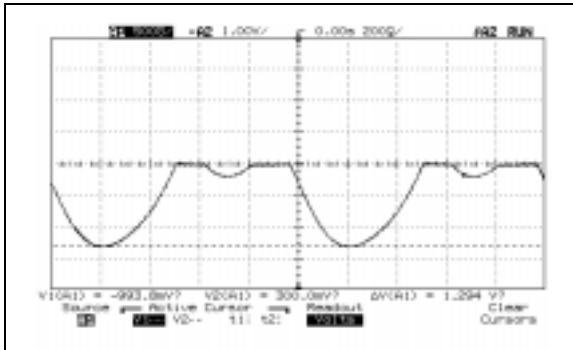
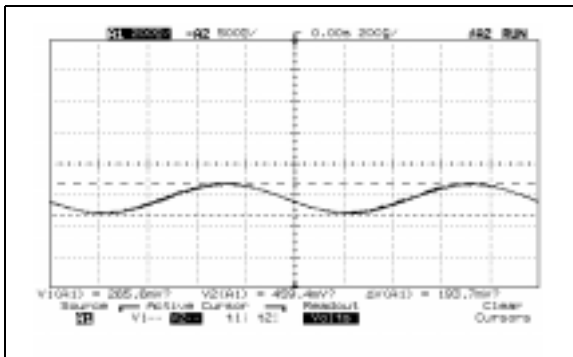


FIGURE 5: NORMALLY DRIVEN CRYSTAL



Purpose of Resistors

R_S is a series resistor that is selected to prevent overdriving the crystal. It is not often needed if gain (Clock mode), C_1 and C_2 are selected properly. If the circuit is being overdriven and a lower gain Clock mode cannot be selected, then adding impedance with R_S can decrease gain. This overdrive can be visually demonstrated by looking at the Osc-Out pin, which is the driven pin, with an oscilloscope. Connecting the probe to the Osc-In pin will load the pin too much and negatively affect performance. The output signal should not be clipped or squashed. Overdriving the crystal can also lead to the circuit jumping to a higher harmonic.

R_S is typically 40 K ohms or less, but is almost never more than 100 K ohms. If the value for R_S is too high, then the high impedance input side of the amplifier may be more susceptible to noise, very much the same way a pull-up resistor on an input pin is normally kept below about 50 K ohms to prevent noise from having enough strength to override the input.

Note: Remember that a scope probe adds its own capacitance to the circuit, so this may have to be accounted for in your design, (i.e., if circuit worked best with a C_2 of 20 pf and scope probe was 10 pf, a 30 pf capacitor may actually be called for here). A J-fet input probe works nicely for measurements like this.

Recall that the external circuit is supposed to provide 180 degrees of loop delay. The amplifier provides 180 degrees, or more. In some unusual cases, if the output from the amplifier is not delayed enough through the oscillator circuit to achieve its portion of the delay then the oscillator may oscillate at a lower voltage. This can be caused by high gain, which creates faster edge rates that reduce delay. Upon first inspection this can appear to be a paradox, because increased gain can sometimes result in reduced signal. In that case, it is possible that increasing R_S will increase the phase delay of the feedback circuit, bringing it in line with being 180 degrees out of phase between the amplifier input and output, and oscillation voltage may actually go up, despite the expected decrease in gain. Think of adding two sine waves together. If the waves are the same frequency, the same amplitude and are in phase, then the result of adding the two signals together is a sine wave of the same frequency with a gain of twice the amplitude. If one of the input sine waves is shifted 60 degrees from the other then the sum of the two will still be the same frequency but the gain will now be considerably less than double the amplitude. (Try this in a spreadsheet if you would like to get a clearer picture). We will see this in one of the lab examples later on. The final circuit must be evaluated thoroughly for these marginal issues to ensure a robust design. Generally, the crystal responds to its resonant frequency so well that other components have minimal affect on the resulting frequency.

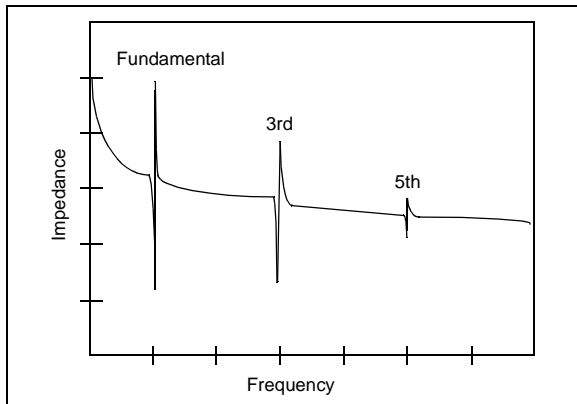
RF_{EXT} is selected to aid in start-up. RF (an internal Feedback FET) provides unfiltered feedback between the output and input of the amplifier. Oscillators require some kind of "kick" to get them started ringing. Before the oscillation begins, noise must be amplified to cause the amplifier to begin generating a signal. Impedance of RF is typically between 5 M ohms and 30 M ohms for IC-based oscillators tuned for crystals. Once oscillation at the resonant frequency is achieved, the impedance of the feedback circuit through the crystal is much lower than the path provided through RF , and the noise no longer affects oscillation. If more noise is needed to assist start-up (which is often the case for resonators) an external feedback resistor, RF_{EXT} can be added. RF_{EXT} is typically between 1 M ohms and 5 M ohms.

Again, RF_{EXT} is most often needed for resonator circuits. In almost every case where a problem with start-up occurred in a resonator-based oscillator circuit, adding RF of 1 M ohm solved the problem.

Overtones

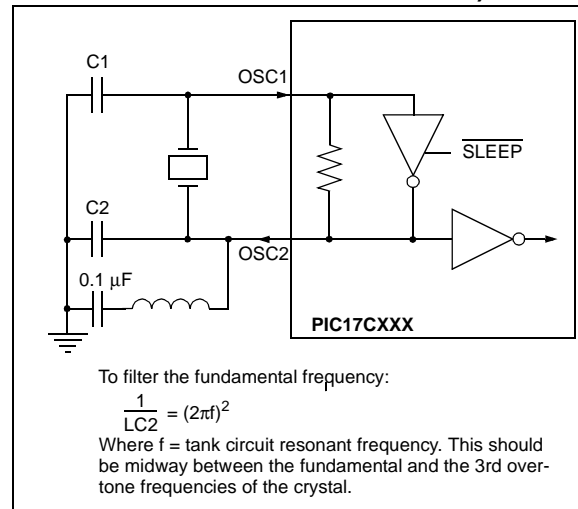
It is possible for a crystal or resonator to oscillate in a higher overtone frequency if the loop gain of the oscillator circuit is greater than one at lower frequencies, and at least unity at the overtone frequency. Electrical overtones come at 3X, 5X and odd multiples of the resonant frequency, as shown in Figure 6. In some cases mechanical overtones can also be achieved at even multiples of the fundamental frequency. In the lab we have seen oscillators functioning at combinations of these overtones, such as the sixth harmonic.

FIGURE 6: QUARTZ CRYSTAL OVERTONE FREQUENCIES



Overdriving the crystal can also cause RF etching of the lead contacts, removing weight from the crystal slab and can cause the frequency to drift (usually drifting up) over time. Since the crystal is actually moving, or ringing, at the resonant frequency, overdrive can also cause the crystal to physically destroy itself. These problems can be prevented through proper selection of C1, C2, and Rs. The circuit shown in Figure 7 is taken from the PIC17C756 Data Sheet, since that device oscillates at over 30 MHz where overtone crystals are the norm.

FIGURE 7: CRYSTAL OPERATION, OVERTONE CRYSTALS (XT OSC CONFIGURATION)



Crystals higher than 20 or 30 MHz are often sold as overtone crystals. This means the oscillator circuit must provide enough gain to drive the crystal into overtone oscillation. Theoretically, frequency starts high and falls back to the highest resonant frequency where unity gain is achieved. In some cases, a filter circuit may be needed to dampen the primary resonant frequency. An LC from the oscillator output pin to ground can filter lower harmonic frequencies to ground.

Resonators

Resonators are typically made out of layered ceramic (instead of quartz, as with a crystal). They can be manufactured at a lower cost than quartz crystals and have performance characteristics that are good enough for many, if not most, applications. A crystal must be held so that it can oscillate uninhibited and is therefore generally suspended on leads within an open can. A resonator is a more physically solid design with a lower mass substrate which is less fragile than quartz crystal. The resonator substrate is mounted more directly in its casing and dipped in a coating like that of a ceramic capacitor and so may offer greater shock resistance. Resonators are usually less effected by overdrive, which can allow the circuit designer greater margin in allowing higher gain than needed to cover higher temperatures. As with all anecdotal advice, the best course is to test your circuit to assure you have achieved the desired operational ranges. Resonators are also offered in packages which already contain the capacitors, which come at a reduced cost since ceramic resonators are made in similar processes as ceramic capacitors and come in similar packaging compounds.

Therefore, resonators can be manufactured with reduced overhead at a lower cost than a crystal and separate capacitors. However, when it comes to meeting needs of outright accuracy, generally a crystal is selected.

There are two important electrical differences between a resonator and a crystal. In Figure 8, taken from a Murata Erie Application Note, you will notice that the impedance of the resonator is lower than that of the crystal and that its frequency response is wider. While a crystal's ESR may be 20 to 1000 ohms, a typical resonator will be in the range of 20 to 150 ohms. The frequency of a typical resonator is less accurate than that of a typical crystal. At start-up, the resonator's lower impedance develops a lower voltage across it over a wider frequency range, which can make it more difficult

for the oscillator to 'find' the fundamental frequency and start oscillation. Getting a noise signal fed back to the input from the output becomes more important. The high impedance often used in IC oscillators (tuned for crystals) for the internal feedback FET (RF in Figure 9) does not help the situation, since little noise will reach the amplifier input to assist in start-up. This can be helped if the feedback impedance is made lower. For these reasons a 1 Mohm resistor, RFEXT, shown in Figure 9, is usually placed across the oscillator terminals to provide more feedback at start-up when using resonators. The diagram also shows the placement of the series resistor temporarily placed in the circuit to measure power, drawn in dashed line, not to be confused with RFEXT.

FIGURE 8: DIFFERENCES BETWEEN A CERAMIC RESONATOR AND A QUARTZ CRYSTAL

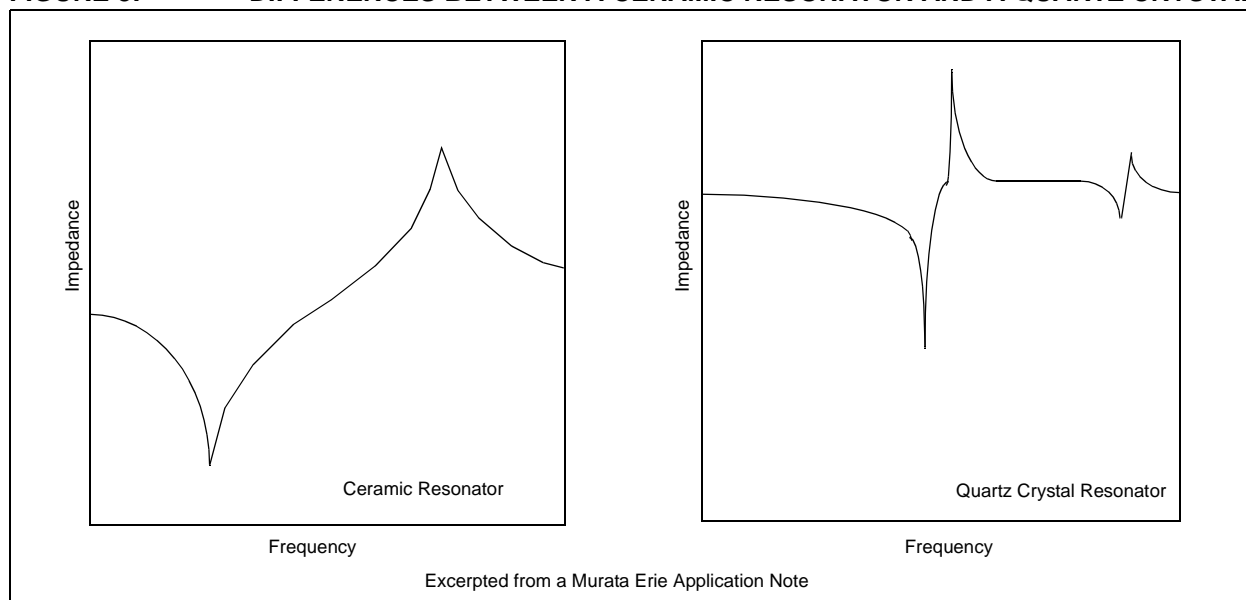
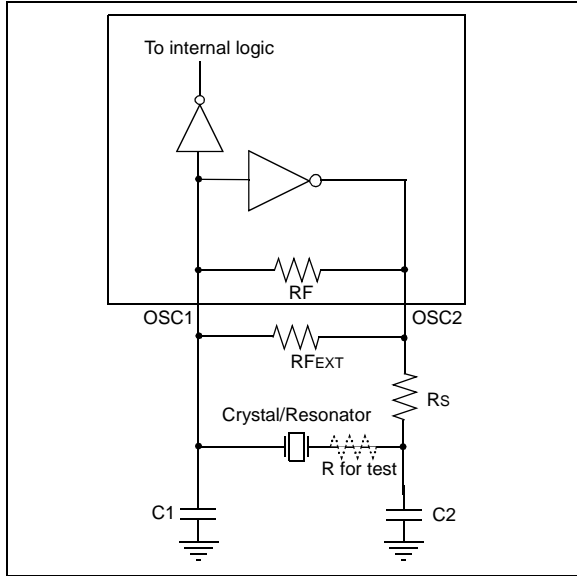


FIGURE 9: CRYSTAL/RESONATOR CIRCUIT



To assist in amplifying start-up noise, it may also be helpful to use a higher Gain mode. For example, at around 3.8 MHz, it is often beneficial to switch to HS mode for a resonator; whereas, a crystal can achieve oscillation in the lower gain XT mode. Again, it is almost always recommended to use an external R_{FEXT} of 1 M ohms if the built-in R_F is greater than 5 M ohms (as is the case for PICmicro R_F values).

As mentioned earlier in this document, gain can be reduced with higher capacitance, so R_s is not often needed in resonator circuits (an R_s can reduce power consumption, however). This is especially true since overdrive has little or no effect on resonator life, the exactness of the frequency is often less significant in resonator oscillators, and since resonators are used in cases where reduced cost is a main goal.

Examining the Oscillator Output Signal

Once you have selected the components you will start with, the next steps are to examine the performance of the oscillator circuit and to alter the circuit as needed until the oscillator performs satisfactorily in all expected environments. On an oscilloscope the Osc-Out signal should be a nice clean sine wave that easily spans the input minimum of the clock-input pin (as much as 4V peak-to-peak for a 5V V_{DD}). An easy way to check this is to test the circuit at minimum temperature and maximum V_{DD} (that the design will be expected to perform under) then examine the output. This should be the maximum amplitude of the clock output. If there is clipping, or the sine wave is squashing or non-sinusoidal near V_{DD} and V_{SS} , and increasing load capacitors will risk too much current through the crystal or push the value too far from the manufacturer's load specification, then add a trimpot between the output pin and C_2 . Adjust the trimpot until the sine wave is clean. Keeping the signal fairly close to maximum amplitude at this low

temperature and high V_{DD} combination will assure this is the maximum amplitude the crystal will see and prevent overdriving of the oscillator circuit. An R_s of the closest standard value can now be inserted in place of the trimpot. Values for R_s are almost always less than 50 K ohms, but should probably never be more than 100 K ohms or you risk making the clock more susceptible to noise. If you find a value this high is needed to prevent overdriving the crystal, try increasing C_2 to compensate. Try to get a combination where R_s is around 50 K or less, and load capacitance is not too far from the 20 pF or 32 pF manufacturer specification.

Start-Up

The most difficult time for the oscillator to start-up is waking up from SLEEP. This is because the load capacitors have both partially charged to some quiescent value and phase differential at wake-up is minimal (although some noise is created internally by the wake-up logic). Also, the power supply has normally reached a quiescent state and is not providing any noise to assist in starting the oscillator. Thus, more time is required for stable oscillation. Start-up on power-up is normally quite easy, since supply noise (and start-up noise from other components before they have reached a quiescent state) provide ample noise input to start the oscillator ringing. Remember also that low voltage, high temperatures and the lower frequency Clock modes also impose limitations on loop gain which in turn affects start-up. The worst possible case is a low frequency design (with its low gain Clock mode), in a quiet environment like a low noise power supply or a battery operated device, operating outside the noisy RF area of the city (or in a shielded box), with low voltage (or low battery), on a hot day, waking up from SLEEP. Creating an environment such as this (low

voltage, high temp, shielded, wake-up from SLEEP) is a good test to see if your circuit has good start-up characteristics.

As mentioned previously, a number of things can be done to assist start-up. These include:

- A 1M to 5M ohm resistor placed across the oscillator terminals to provide more feedback at start-up (RFEXT in Figure 9).
- Selecting a higher Gain mode, to increase amplification of noise at start-up.
- Unbalancing the capacitors by making one a higher capacitance than the other (usually C2 is made higher than C1).

Higher gain causes more noise to be fed back into the signal and creates a faster start-up edge that can help reduce start-up time. C2 may have to be increased or decreased and/or an Rs added to prevent overdriving the crystal.

In the very rare cases where your circuit is already expected to operate in an exceptionally quiet environment (i.e., with voltage at the minimum and temperature fairly high) you may have to provide some start-up noise yourself. Otherwise, there is not much margin left to test to and assure a fail-proof design. There is an old designer's tip that a cheap RS or RFEXT resistor, such as a carbon film or carbon composition resistor, can actually help start oscillation. All resistance generates some amount of noise which, when placed in the crystal oscillator path or on the input, can assist start-up. If you have a button that will be pressed, or some signal to wake up the part, then a capacitor from that signal to the oscillator input can provide the start-up jolt that is needed. This should be a wake-up signal and not a signal that would be generating noise while the circuit is running; otherwise, another technique to eliminate the signal when it was not needed would have to be employed. It is also possible to connect the oscillator circuit grounds to VDD instead, with the benefit of the usual additional noise that is introduced by a VDD reference. This is typically not done, but can be beneficial in certain situations such as this.

It is also possible for a circuit with too much gain to not start-up. This usually happens most often at low frequencies, like 32 kHz, since at high frequencies the high gain is dissipated more easily by the load capacitance.

Other Design Considerations

The actual board design is not covered here in much detail since that subject can become lengthy on its own. Consider studying the related subjects of high-speed design and analog design techniques as well as handling noise and ESD. However, a few tips are worth mentioning:

1. Keep the oscillator circuit trace lengths to a minimum and away from signals that can inject unwanted noise, or may be affected by the signal of the oscillator.
2. Where an oscillator or timer input pin is next to another active output pin, consider routing one of the signals away from the chip and the other towards the underside of the chip, so that they are adjacent only at the pins themselves and the traces are never adjacent.
3. Avoid sharp angles in the traces, which can cause reflections. (Though this is sometimes disputed).
4. Board manufacturing and assembly techniques can also affect oscillator performance. For instance, there have been several occasions where the oscillator failed to start and the failure was traced back to contamination on the board. Contaminants on surface mount boards are especially a problem, as contaminants become trapped under a surface mount crystal or resonator. If the contaminant is at all conductive, or can ionize in humidity (such as a salt-based board wash), then a second feedback path between the oscillator input and output is created which can prevent start-up or affect the running oscillator performance.

The Final Test

With all of the parameters and conditions that must be looked after and the shortage of all the data necessary for a reliable mathematical model for an oscillator, it may seem quite difficult to design an oscillator circuit that can be assured to run in a wide range of environments. The good news is that if you find the ideal "sweet spot" for the oscillator you can overcome temperature, voltage and part-to-part drift. If you have a marginal design and do not know if these factors can cause the circuit to malfunction unexpectedly. If you identify the margins for the environment that your circuit will run in and verify its performance, within or beyond those margins, you should find that the oscillator performs as desired over a very wide range of changes. The most important point is to be aware of where these marginal areas exist, then verify that your design works correctly in all cases. Once that is done there is very little left to worry about. We suggest that designers test their circuits under the worst possible conditions. In fact it is possible to exceed the operating specification of the part, for purposes of these tests, perhaps while holding it in RESET to prevent improper execution from causing power consumption problems.

The following tests are suggested:

- Start by selecting C1 and C2 per the Microchip data book.
- Test at maximum VDD and Lowest temperature.
- Test at minimum VDD and Highest temperature

- Test for wake-up from SLEEP with high temperature, low voltage and quiet DC supply.
- Adjust C1, C2 and Rs as needed and repeat tests until satisfactory results are achieved

Check that the output sine wave is not clipping in the highest gain environment of highest VDD and lowest temperature. Also, make sure that the sine output amplitude is great enough in the lowest gain environment of lowest VDD (and highest temperature) to cover the logic input requirements of the clock. A value of 4V peak-to-peak is usually fine, but refer to the data sheet for the final specification requirements. Then, at the highest temperature, with the lowest VDD the circuit will have to run at, running from a quiet battery if possible, in as quiet an environment (RF and electrically speaking) as your board will see, test the part to make sure it wakes up from SLEEP. If all this checks out and your capacitance values are low enough, (and within range to prevent unnecessary power consumption) then you should have a clean, trouble-free oscillator design.

A Note on External Clocks

If the PICmicro oscillator is not being used and the device will be driven from an external clock, be sure to set the Clock mode to something other than RC mode, since this mode will fight with the injected input. Ideally, you would select the mode that corresponds to the frequency injected, but this is of less importance here since the clock is only driving its internal logic and not a crystal loop circuit. It may be possible to select a Clock mode lower than would be needed by an oscillator circuit, and thereby save some of the power that would be used exercising the inverting amplifier.

A Demonstration of Oscillator Circuit Performance Problems.

A number of tests were conducted in the lab to demonstrate the various problems encountered with marginal oscillator designs. Start-up, overdrive, under-drive, harmonics and ideal characteristics were all evaluated and the results captured on an oscilloscope. In this series of tests, the start-up performances of a number of circuits were tested. The test circuit setup was as follows:

Test Circuit Setup

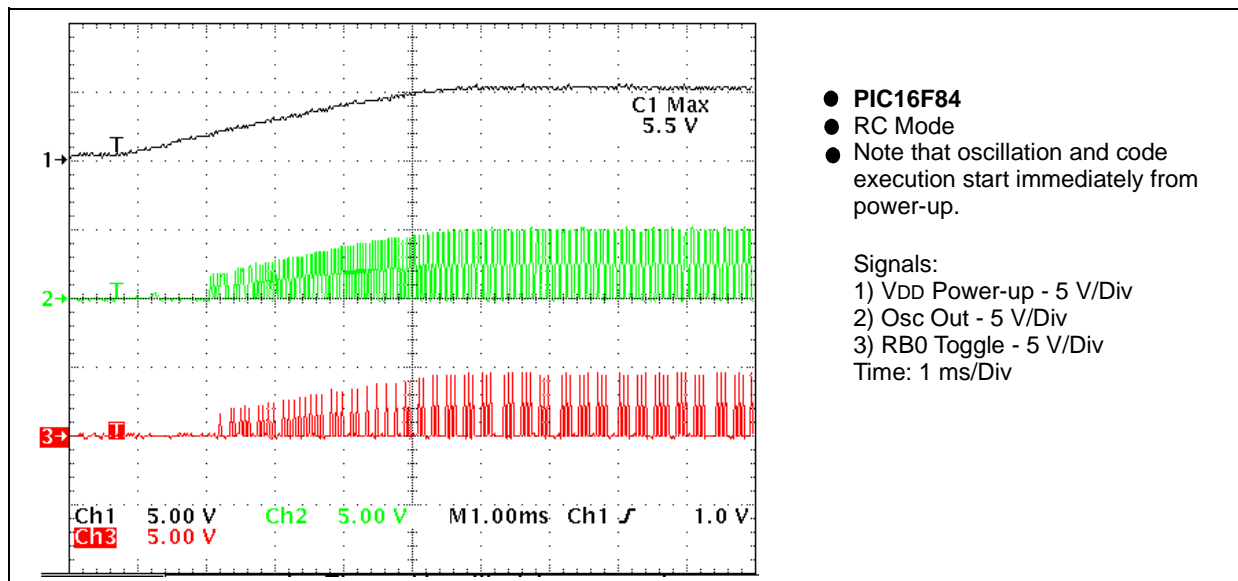
- A fixed DC supply and a switch created VDD ramp up. To assure equivalent comparisons, anything without a consistent power-up ramp was rejected.
- Code was written to initialize ports and start toggling RB0 immediately to illustrate code start-up time.
- The Oscillator output pin, Osc 2 or Osc Out, was measured and displayed against the other signals, VDD and RB0 (toggling with code execution).
- The PICmicro enters SLEEP mode upon press of an input switch. WDT is disabled, so wake-up from SLEEP only occurs on MCLR Reset.

This test circuit assures a consistent power-up ramp so that start-up can be measured with the same reference point. All signal images were captured from an oscilloscope. If there is an apparent difference in the VDD start-up ramp, it is solely because of the time-base settings of the scope setup. It should also be noted that, in many cases, the captured oscillator sine wave is not necessarily drawn accurately compared to the oscillator frequency as there are some display harmonics depending on the screen refresh rate and resolution. Counting cycles will not be an accurate measurement of apparent frequency. This is specifically where the scope refresh rate is slowed to very low speeds to observe oscillator ring-up. Where the signal is being examined for its frequency content, the signal was isolated at a rate compatible with accurate screen display. In many cases, capacitors, Gain mode and other parameters were forced out of specification to demonstrate the ill effects of an improperly designed circuit. Where improper performance is pointed out, the design could easily be remedied with the advice already given above.

Baseline Comparison - RC Mode

The fastest possible start-up is the RC or EC Oscillator modes (see Figure 10). Here we see the oscillator starts up immediately with the power-up ramp. Code execution also begins immediately since there is no 1024 start-up count for RC mode.

FIGURE 10: BASELINE COMPARISON - RC MODE

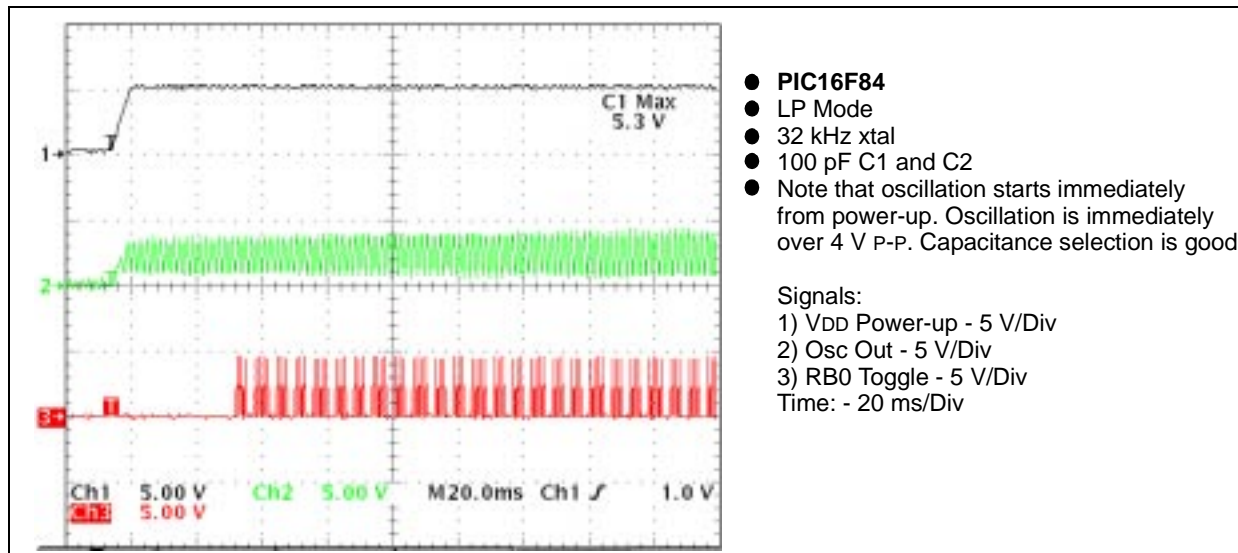


Ideal Power-up Start-up

Here a PIC16F84 oscillator starts up nicely (see Figure 11). The PIC16F84 has a fairly high gain LP mode, which means that it has a fairly fast start-up, but at very low frequencies, perhaps 32 kHz, it has higher drive strength than necessary to sustain oscillation and may overdrive the crystal. The external circuit must

therefore compensate for this by loading the circuit with high capacitance or with R_s . In most of this series, where crystals were used, high capacitance was used (100 pF here) to demonstrate the gain limiting effects of capacitance to keep the number of variables to a minimum, though an R_s is often preferable.

FIGURE 11: IDEAL POWER-UP START-UP

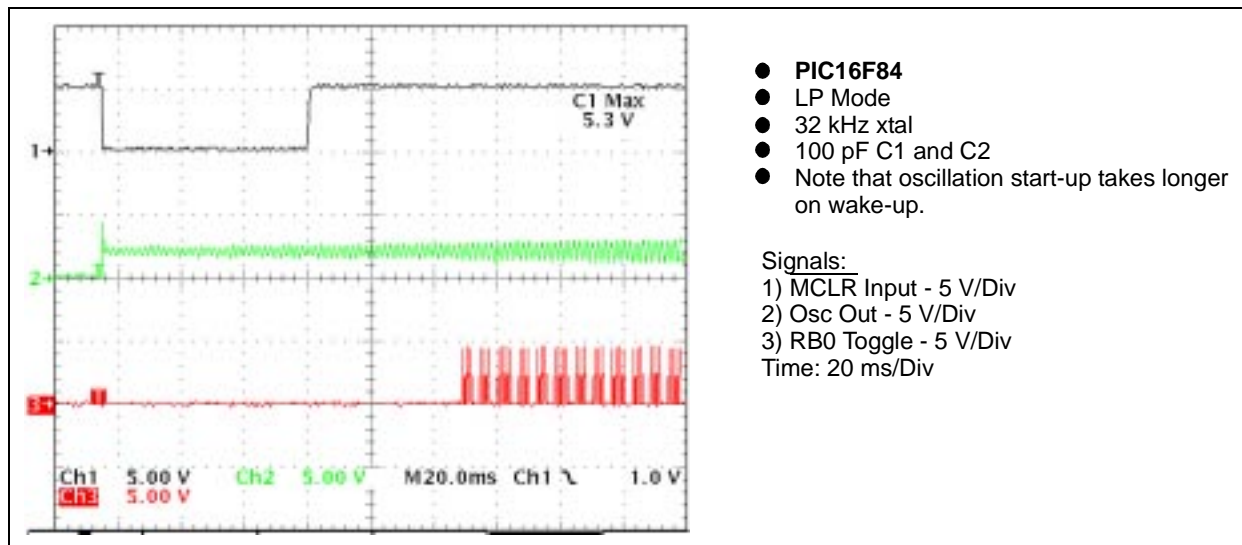


Wake-Up from SLEEP

Wake-up from SLEEP is the worst possible case for oscillator start-up (see Figure 12). Power-up noise and other switching noise created by the power-up process creates the necessary start-up input needed to start oscillation. When the circuit has been powered already and the device is put to SLEEP, there is little or no circuit noise. Therefore, the oscillator can take longer to

start-up. It is also interesting to note that the oscillator starts oscillating at the beginning of the $\overline{\text{MCLR}}$ low pulse. If there is ever any doubt as to the oscillator start-up, the device can be held in RESET for as long as it takes to obtain sustained oscillation. (Note: this is not usually the preferred solution, and is rarely necessary).

FIGURE 12: WAKE-UP FROM SLEEP

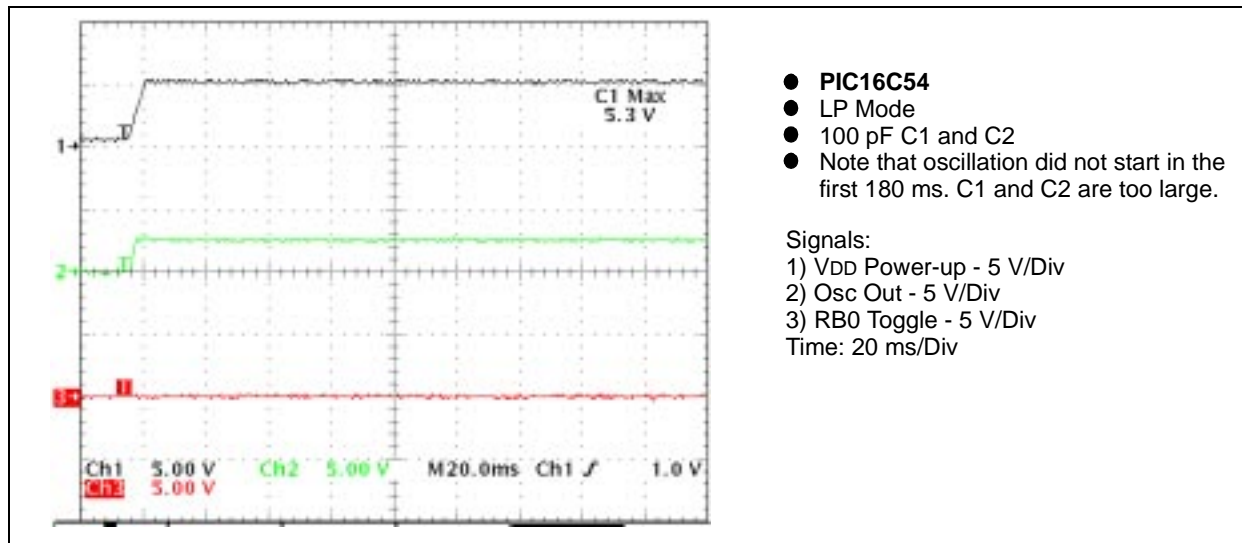


Capacitor Selection - No Start-up

Notice that this circuit (see Figure 13) has been configured such that a PIC16C54 cannot achieve sustained oscillation with the same circuit that worked for the PIC16F84. That is because the PIC16C54 has lower gain in LP mode than the PIC16F84 had. Differences in gain often occur between parts of different families and

different processes. The PIC16C54 is from an older OTP process and the PIC16F84 is from a newer FLASH process, for example. It should never be assumed that a circuit that worked in one part or environment before would continue to work in a different part or environment.

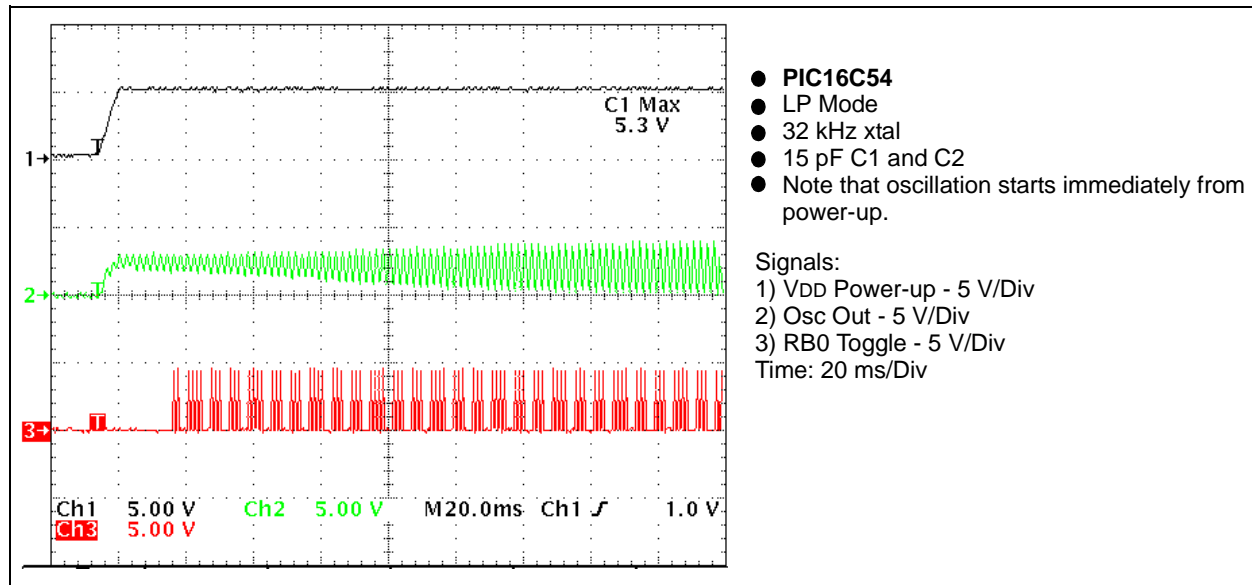
FIGURE 13: CAPACITOR SELECTION - NO START-UP



PIC16C54 vs. PIC16F84 Gain/Start-up

In Figure 14 we see the PIC16C54 achieving excellent start-up with 15 pF capacitors, as opposed to 100 pF used for the PIC16F84. Otherwise, the circuit is the same, with the same Gain mode at the same frequency.

FIGURE 14: PIC16C54 VS. PIC16F84 GAIN/START-UP

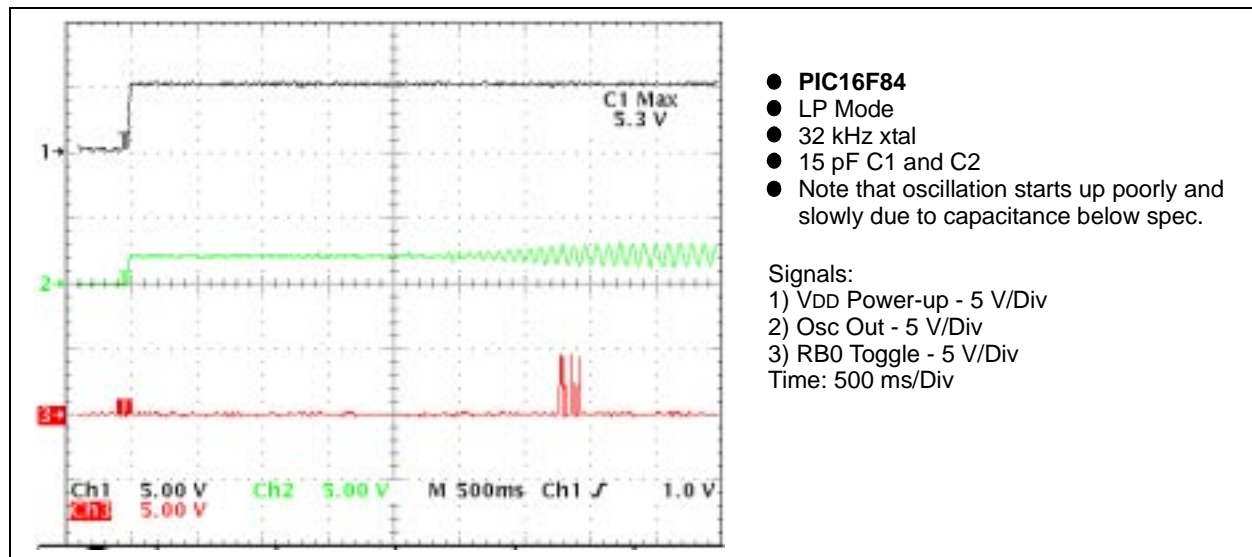


PIC16C54 vs. PIC16F84 Gain/Start-up

Now we see the PIC16F84 with the same lower capacitance values that worked for the PIC16C54 (15pf), and it cannot start-up. It is interesting to note that it appears that there is not enough gain to start oscillation, when in fact there is too much gain. Without the appropriate

360 degrees of total loop phase shift, the oscillator cannot even start-up in this case. Higher capacitance or R_s is needed to reduce gain.

FIGURE 15: PIC16C54 VS. PIC16F84 GAIN/START-UP

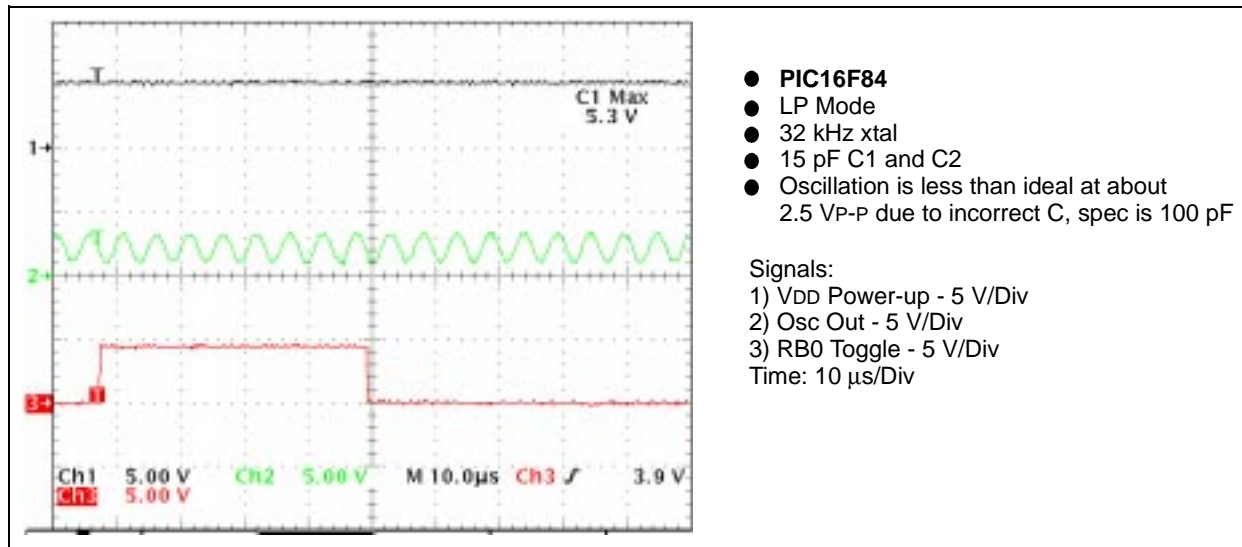


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Capacitor Selection - Low VP-P

Here we demonstrate in a progression of capacitance increases the effects on oscillator peak-to-peak swing (see Figure 16). We increase capacitance until we achieve satisfactory margin peak-to-peak. Here we have started with a fairly low value of 15 pF capacitors.

FIGURE 16: CAPACITOR SELECTION - LOW VP-P

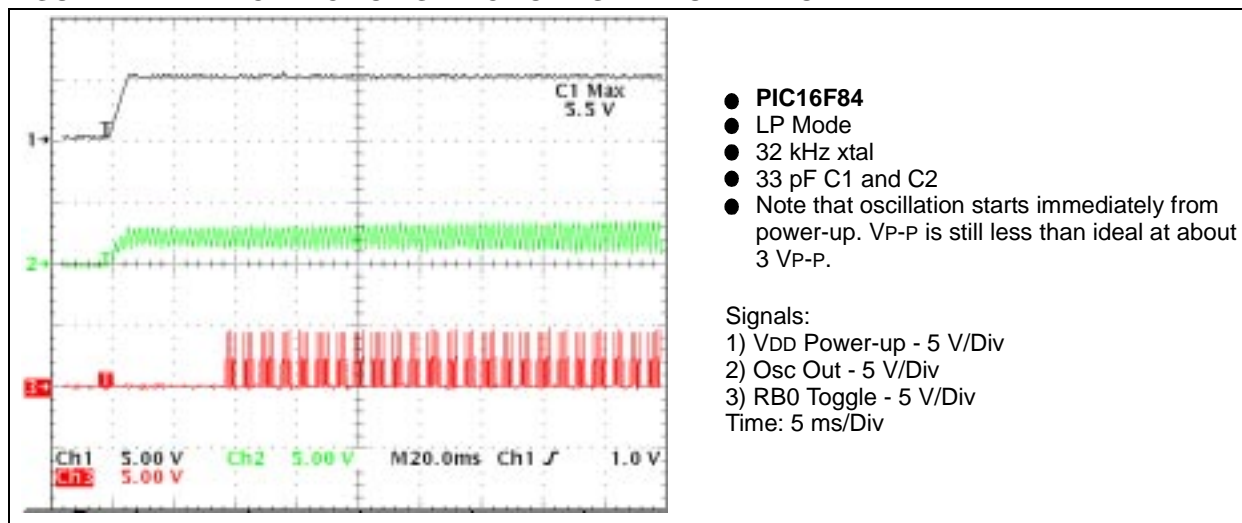


Capacitor Selection - Start-Up Improved

In Figure 17, we increase to 33 pF and see an improvement. Again, notice that it appears as though there is not enough gain. Too much gain means not enough

phase shift, which means the signal does not arrive back at the input at the proper moment to achieve maximum amplification. So in fact, it IS a low gain situation, caused by too much gain!

FIGURE 17: CAPACITOR SELECTION - START-UP IMPROVED

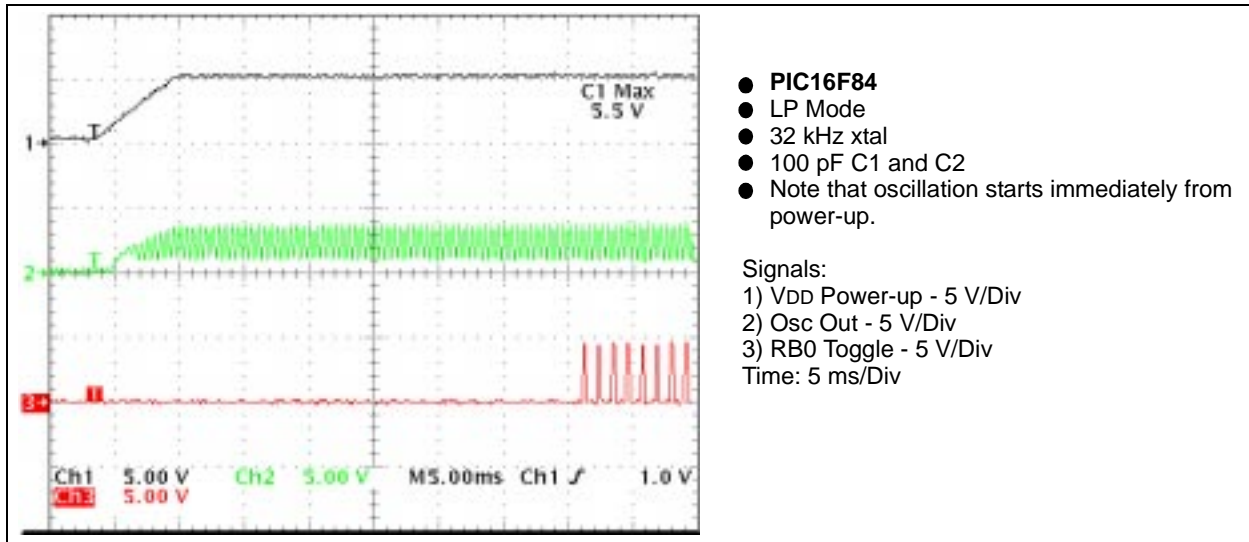


Capacitor Selection - Good Start-Up

Finally, at 100 pF, we have achieved ideal oscillation (see Figure 18). Note that a series resistor R_S could have been used to cause more phase delay and lower gain to improve the circuit, instead of just loading it with

capacitance. In fact, many crystals may not handle higher wattage dissipation and can be damaged. For this reason, it is preferable to switch to using R_S once capacitance values start to get too high.

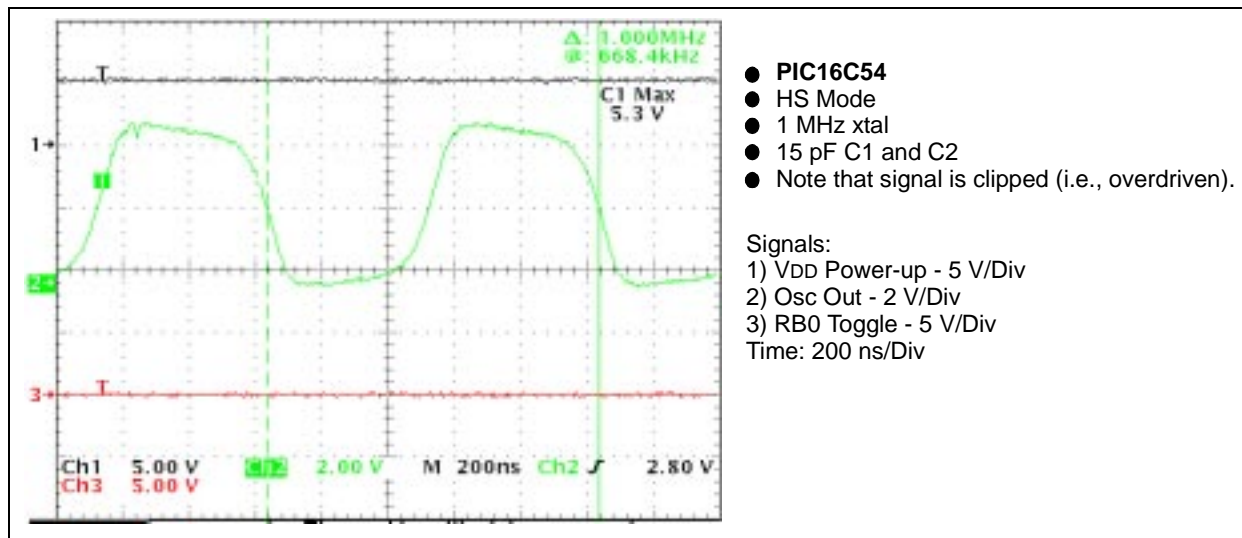
FIGURE 18: CAPACITOR SELECTION - GOOD START-UP



OVERDRIVEN CRYSTAL

Here we have intentionally selected a higher Gain mode than necessary to demonstrate what overdrive looks like (see Figure 19). Notice the clipping at the rails. The signal should be symmetrical and sinusoidal.

FIGURE 19: OVERDRIVEN CRYSTAL

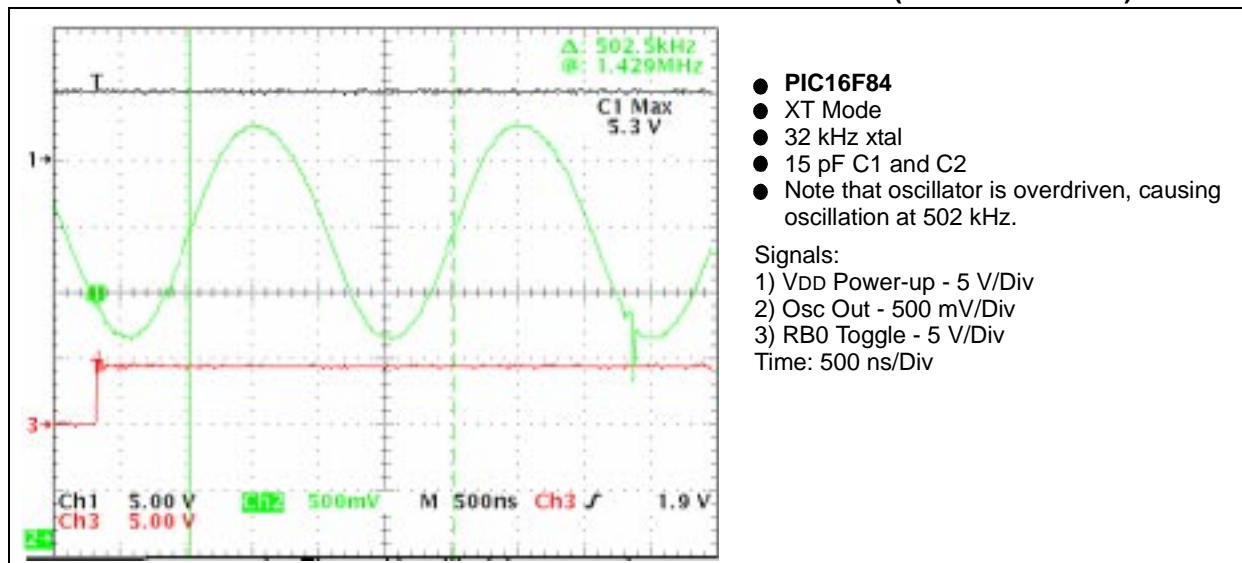


Overdriven Crystal at Higher Frequency

Here again we are providing too much gain for the circuit (see Figure 20). Recall that for the PIC16F84 in LP mode at 32 KHz, 100 pF capacitors were needed to achieve ideal oscillation. Here we have pushed the gain up even higher into XT mode to demonstrate what

happens when the crystal is overdriven. In this case, the 32 kHz crystal is oscillating at 502 kHz. This is a 15th overtone. Notice also the noise spikes that occur regularly, which are components of even higher overtones.

FIGURE 20: OVERDRIVEN CRYSTAL AT HIGHER FREQUENCY (15TH OVERTONE)

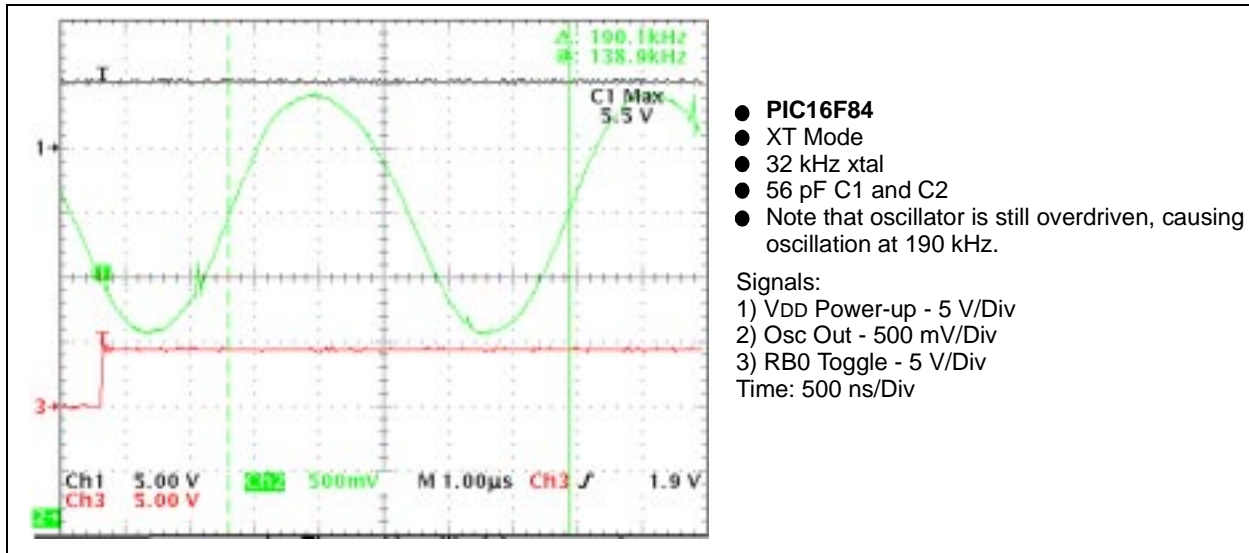


Another Overdriven Crystal at Higher Frequency

Here we increase the capacitance to 56 pF, which loads the circuit and reduces gain and brings the overtone oscillation down to 190 kHz (see Figure 21). This

is approximately a 6th overtone, perhaps a combination of the odd electrical overtone and the even mechanical. There are still noise spikes from higher overtones.

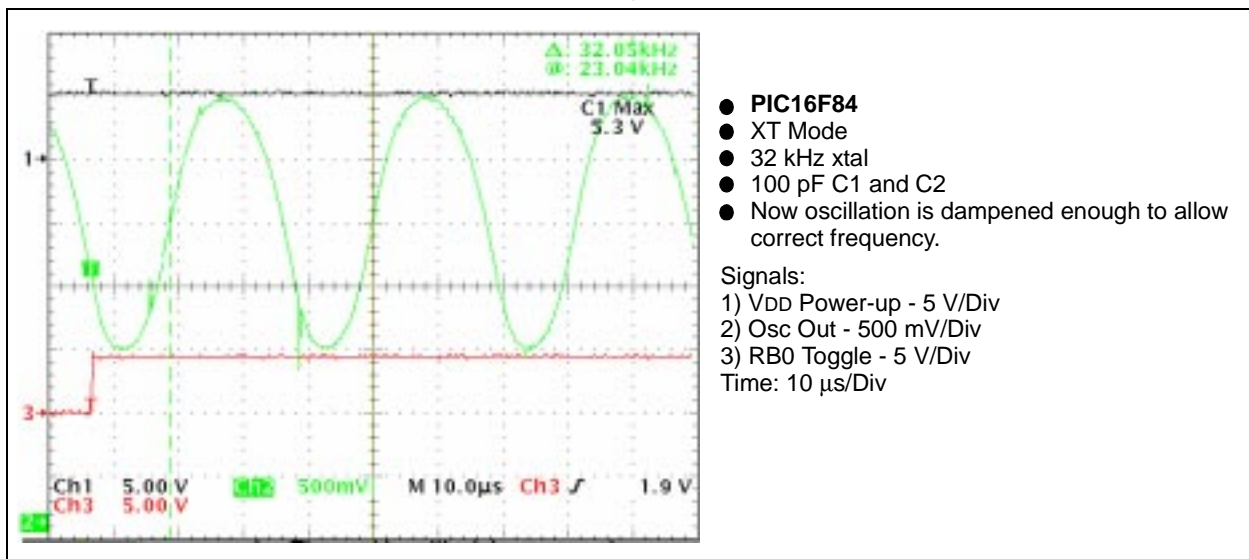
FIGURE 21: ANOTHER OVERDRIVEN CRYSTAL AT HIGHER FREQUENCY



Overdriven Crystal Frequency Corrected

Finally, at 100 pF we have achieved the correct frequency (see Figure 22). Notice though the significant noise spikes at the higher frequency components.

FIGURE 22: OVERDRIVEN CRYSTAL FREQUENCY CORRECTED



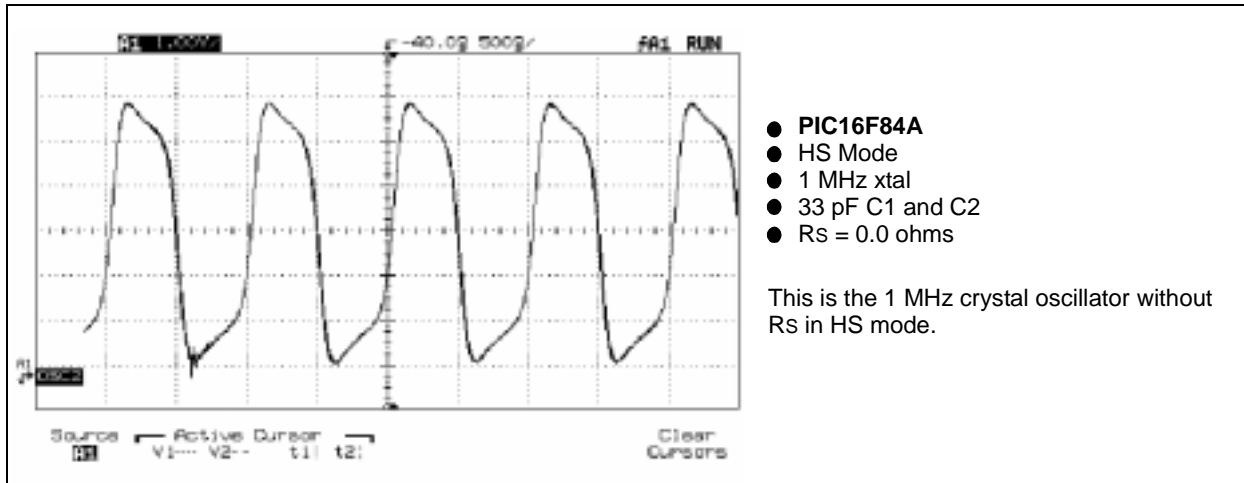
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Overdriven Crystal Corrected with Rs

Here we have intentionally selected a higher Gain mode than necessary to show what overdrive looks like and to demonstrate correcting it with Rs (see Figure 23). The Microchip data book recommends XT

mode for a 1 MHz crystal in this case, but HS mode was selected to demonstrate overdrive. Notice the deformation at the rails. The signal should be symmetrical and sinusoidal.

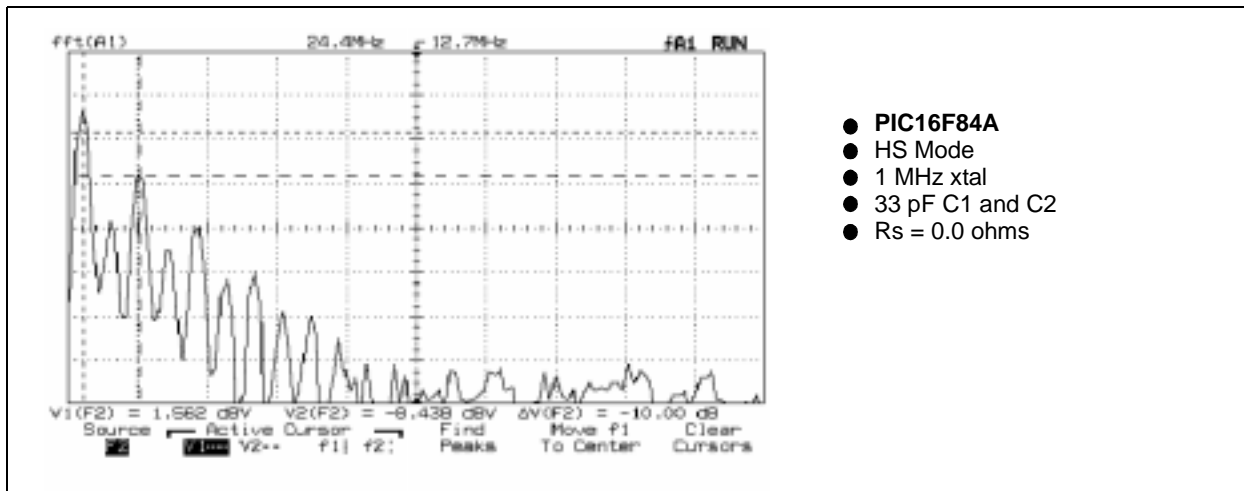
FIGURE 23: OVERDRIVEN CRYSTAL NOT YET CORRECTED WITH Rs



The same circuit as used for Figure 23 has its frequency spectrum displayed here using an FFT scope function (see Figure 24). This diagram demonstrates the strength of the harmonics. The circuit is a PIC16F84A with a 1 MHz crystal oscillator without Rs

in HS Gain mode. The FFT plot shows that the primary frequency signal strength is barely above the 2nd and 3rd harmonics. The 3rd is strongest, next to the primary frequency, at only 8 dBV down from the primary frequency.

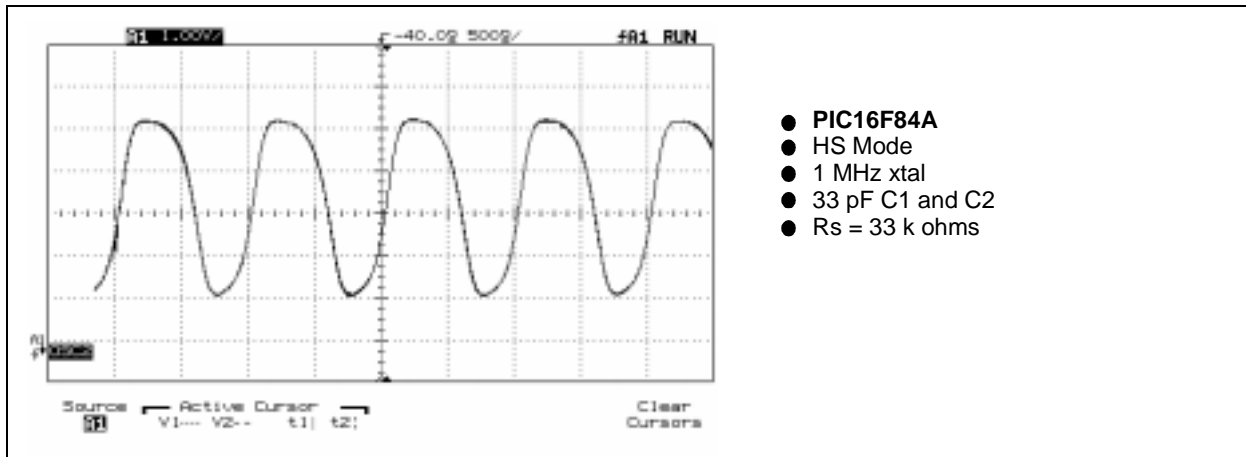
FIGURE 24: FREQUENCY SPECTRUM SHOWING HARMONICS



Now we have added a series resistor, R_s , to the circuit to correct for overdrive (see Figure 25). A test resistor was placed in series with the crystal to measure the drive strength, while a trimpot was used to determine a workable value for R_s . Once the drive strength was reduced to a reasonable level, the trimpot was replaced with the closest standard resistor value, 33 k ohms. Notice that the sine wave is much cleaner now. This

circuit would then be tested over temperature and voltage and for wake-up from SLEEP performance to assure a proper design. This before-and-after situation is the one used in the example to describe measuring power, discussed earlier in this document. Refer back to the diagrams there (Figures 4 and 5) for an example of the power measurement waveforms for these two examples.

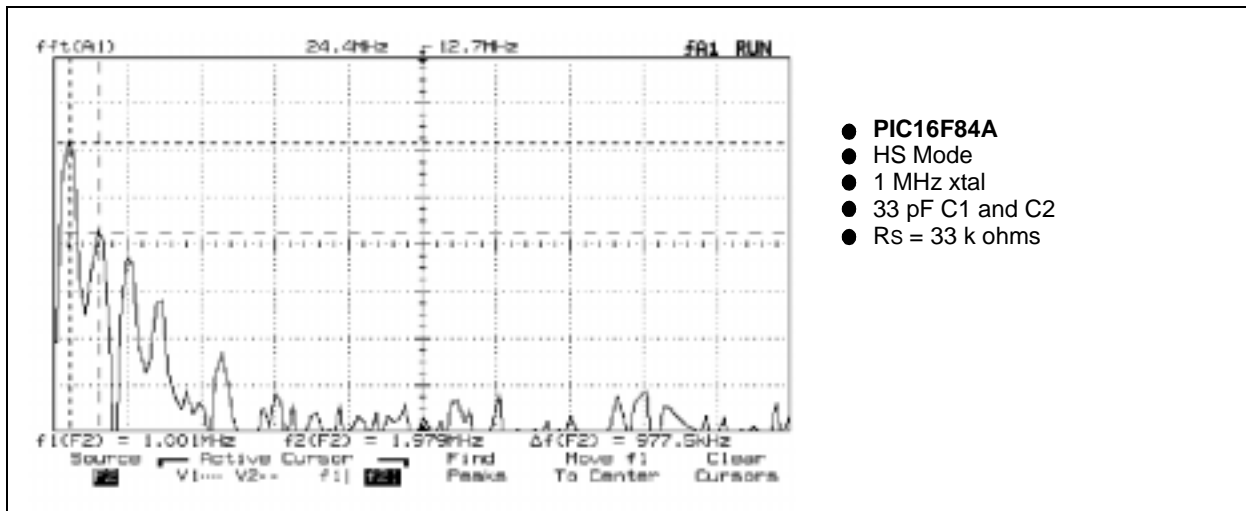
FIGURE 25: SAME OSCILLATOR WITH R_s OF 33 K OHMS ADDED



Here is the same oscillator with the R_s of 33 K ohms added to limit overdrive (see Figure 26). Notice that the FFT displays that the 2nd harmonic is strongest,

but is now improved with the strongest harmonic an additional 10 dBV down, at 18 dBV down from the primary frequency.

FIGURE 26: SAME OSCILLATOR WITH R_s OF 33 K OHMS ADDED



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DEMONSTRATING OSCILLATOR PERFORMANCE OVER TEMPERATURE

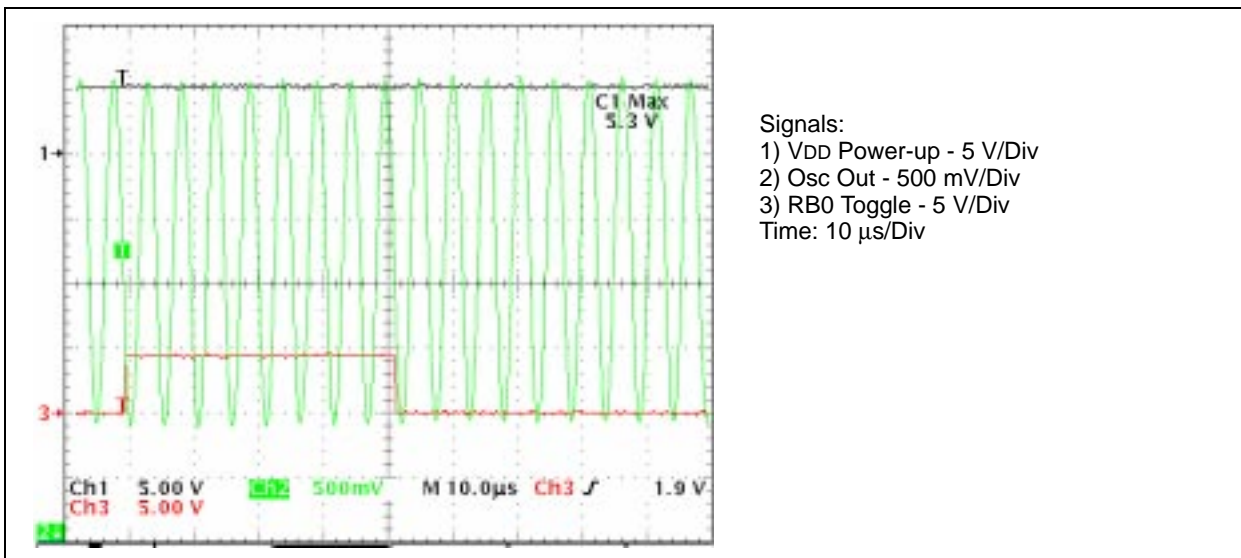
- A Circuit was created with low gain and marginal oscillator performance of 2.5V peak-to-peak at room temperature.
- The result is code that executes at room temperature, but does not function properly at higher temperatures.
- At higher temperatures gain is decreased in the oscillator circuit, due in part to increased R_{DS(on)} in the FETs.
- At colder temperatures, FET R_{DS(on)} decreases and loop gain is increased.

- Temperature can often be used to model the effects of voltage change (and vice versa). This is because lower voltage reacts similarly to higher temperature, as both decrease gain. Conversely, higher voltages and lower temperatures both increase gain.

Marginal Oscillator Circuit at Room Temperature

Here we have intentionally caused the oscillator to oscillate in a marginal mode, with only 2.5V peak-to-peak (see Figure 27). Within this range we can demonstrate very small changes in gain. More gain will increase the signal strength, less will diminish it.

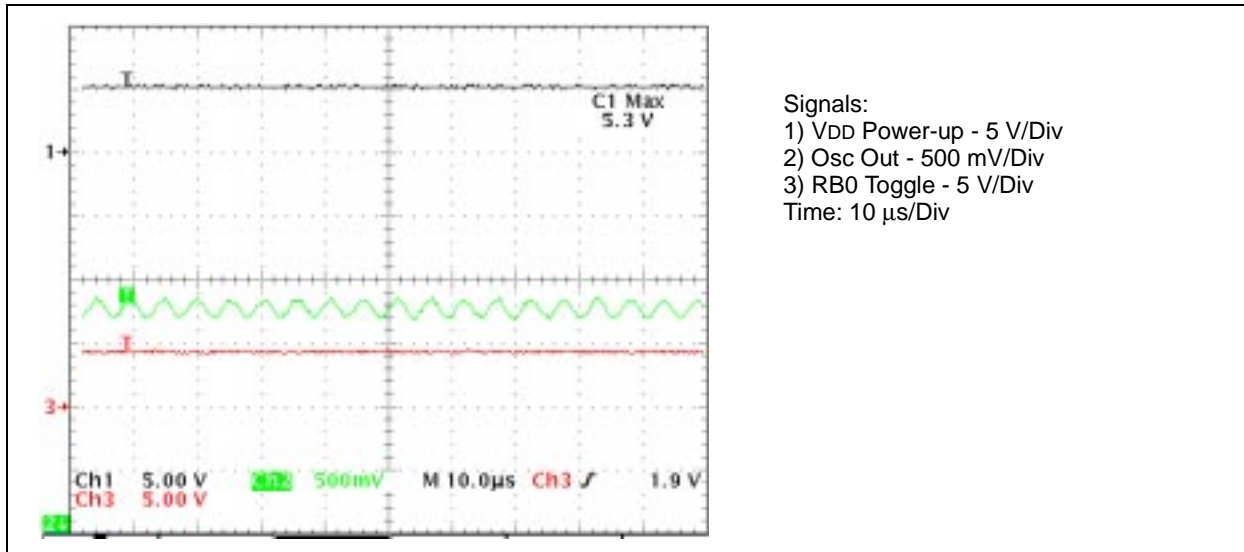
FIGURE 27: MARGINAL OSCILLATOR CIRCUIT AT ROOM TEMPERATURE



Marginal Osc Circuit - Heated

A few seconds of hot air from a heat gun causes the oscillator signal to diminish significantly (see Figure 28).

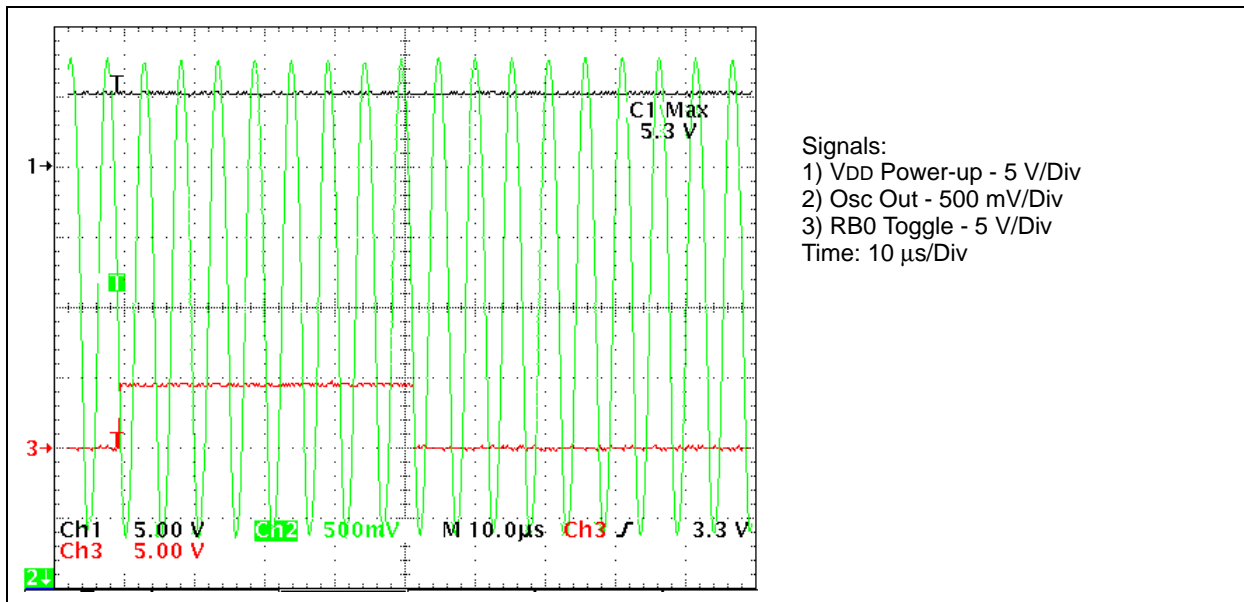
FIGURE 28: MARGINAL OSCILLATOR CIRCUIT - HEATED



Marginal Osc Circuit - Cooled

Here we cool the circuit with a quick shot of cold spray (see Figure 29). Notice that the signal amplitude has increased to about 3.5 V_{P-P}.

FIGURE 29: MARGINAL OSCILLATOR CIRCUIT - COOLED



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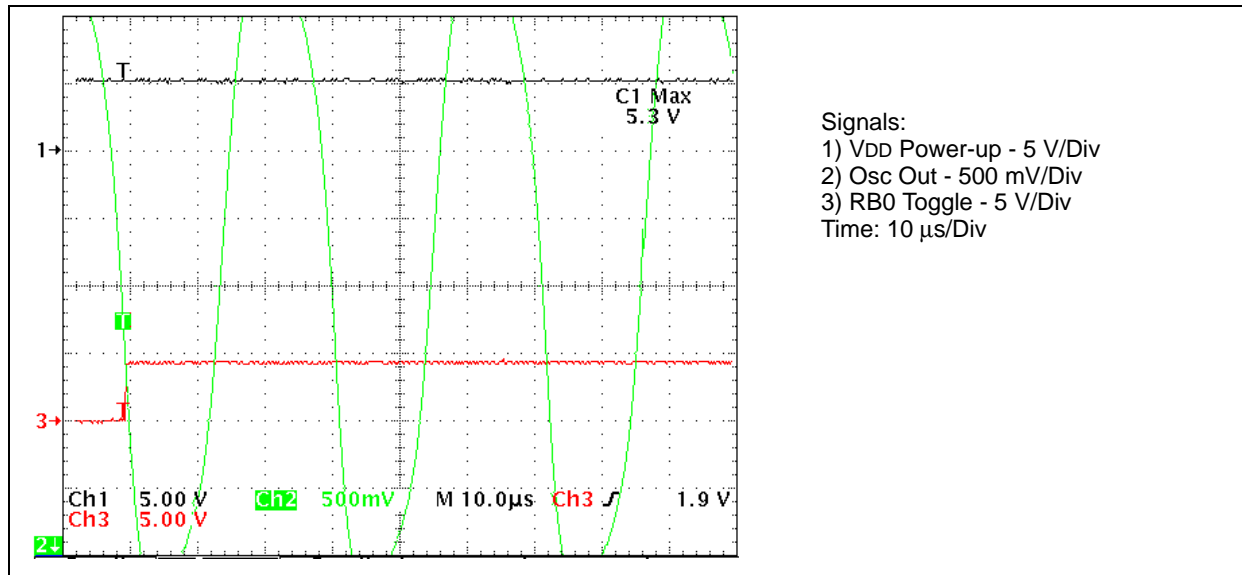
Good VP-P at High and Low Temperature

In this circuit, we designed the oscillator to operate in an ideal fashion (see Figure 30). A heat gun was applied until the board turned brown, then a cold spray canister was nearly emptied onto the circuit. Neither affected the signal amplitude measurably.

The point here is that a marginal circuit may look fine, and then not perform correctly at high or low temperature. An ideal circuit should work perfectly over temperature.

Again, it is also important to know that voltage can often be substituted for temperature, where low voltage causes similar effects as high temperature (lower gain), and high voltage causes similar effects as low temperature (higher gain). Combining high temperature and low voltage is an effective way to identify low gain margin areas. Conversely, tests which combine low temperature and high voltage help isolate high gain and overdrive margins.

FIGURE 30: GOOD VP-P AT HIGH AND LOW TEMPERATURES



IN CONCLUSION

A lot has been said here about the few components that go into the oscillator circuit, perhaps too much, or perhaps not enough. Knowing what to look for is half of the battle. Knowing what to do about what you find is the rest. Many other references exist which explore other aspects of the oscillator circuit, but the information provided here should get you well on your way towards a successful design. Resonator and crystal manufacturers have published excellent material. Mathematical treatises on oscillator designs exist in abundance and can usually be found just by searching the web. Again, manufacturer web sites may provide a large amount of specialized data. Murata Erie and Fox Crystals were both instrumental in providing information used in this Application Note and we appreciate the excellent support we received from both companies. Appreciation is also due to Microchip Technology Analog Design Engineer Scott Olson and Process Engineer Wayne Armstrong, who provided much of the insight into oscillators in general, and PICmicro oscillators specifically. Any mistakes in this publication are almost certainly the author's.

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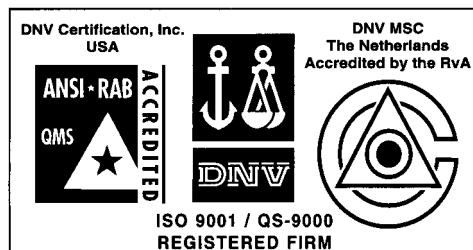
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