HF Helical Resonators for 1 kW TX Power Levels with Very High Q

Operating multiple radios with high power 1 kW linear amplifiers on the same HF band that are also located at the same site presents significant problems with interference. This may be an issue for Field Day (although Field Day operations are now limited to 100 Watts) or it may be an issue for QSO parties where club stations may operate CW and phone on the same band with linear amplifiers. Very high Q HF helical resonators suitable for 1 kW TX power levels can help address this problem using Ultra-Sharp Low-Loss (USLL) filter configurations as previously detailed for 100 W TX power levels. [1] In this paper, high power and high Q helical resonators are detailed using large chambers that are almost 1 foot on a side constructed of aluminum sheeting containing coils about 6.5 inches in diameter made of 3/8” or 1/4” copper refrigeration tubing. This work targets especially 20 meters and 40 meters, but the chambers are usable for very high Q resonators for 160 meters to 10 meters. The detailed steps to construct the large chambers from aluminum sheets are explained as well as construction of the large coils. Investigations and experiments to maximize Q approaching 2000 for 20 meters and to achieve high power operations are presented. The results show the possibility of excellent overall isolation on the same band between the CW segments and phone segments on 40 and 20 meters for high power operations from the same location using separate antennas providing some isolation with cross polarization, end-to-end setups, or similar arrangements. The results also suggest that it is feasible using multiple resonators with appropriate filter configurations to operate with CW and phone on a single shared antenna for 40 or 20 meters but only over small CW and phone band segments in that case due to the very high isolations required of 70 to 80 dB in the filters alone. A 2nd paper provides details on 3 resonator filters for 20 and 40 meters for 1 kW operations providing 20 to 40 dB of isolation between the CW and phone segments of those bands with only about 0.5 dB of loss in the desired band segment. Antennas separated by cross-polarization, end-to-end orientation or other techniques are also important to provide some isolation, as well as high performance radios, proper grounding/bonding, and power supply isolation.

Discussion

Is it possible to use 100 W capable USLL filters placed between a 100W radio and a high power linear amplifier to operate with multiple radios on the same HF band? Experiments using several different radios and a Heathkit SB220 showed that this provides very limited benefit. While a few dB’s of TX noise reduction was measured in the phone band when using a Yaesu 991A radio on 80 meters in the CW band with an SB220 amplifier and an USLL filter placed between the radio and the linear amplifier, the TX noise reduction was much less than the noise reduction directly on the radio output which was 20 to 40 dB. Several factors that probably contribute to this result are noise in the linear amplifier itself and distortion in the amplifier spreading noise into the phone band from the CW band. Better results may be possible with different amplifiers and radios. An alternative is to design and build USLL filters capable of direct operation at 1 kW power levels at the output of the linear amplifier, but that requires very high Q resonators and circuits capable of high RF voltages and currents to minimize losses in the USLL filters where the 1 kW transmit signal is only separated in frequency from the filter’s stop-band by about 100 KHz.

The chambers used in previously built USLL filters for 100 W TX power levels used off-the-shelf aluminum boxes of size 6” x 6” x 6”.[1] In order to about double the Q as limited by the chamber (a target chosen to reduce losses for 1 kW power levels), doubling the size of the chambers appeared appropriate. Helical filter chamber diameter (or box side length) is known to be directly proportional to Q while coil properties are generally a secondary limitation, [2][3] if the coil is made from copper wire or tubing and has dimensions consistent with the chamber. Suitable low-cost aluminum boxes are not known to be available off-the-shelf at 12" x 12" x 12", but aluminum sheeting is readily available at 12" in width. As shown later, shaping aluminum sheeting into the necessary large boxes is quite doable with minimal equipment and modest skills by a ham and the overall cost is reasonable. By using 0.04 inch think aluminum sheeting, a light but mechanically strong chamber weighing only about 5 lbs including the coil results. The large chambers can accommodate coils that are about 6" to 7" in diameter and are 6" to 8" in length. Using 1/4" copper tubing, up to about 16 turns is possible (about 25 uH) and using 3/8" copper tubing up to about 11 turns is possible (about 12 uH). This can support helical resonator frequencies in the range of 7 to 14 MHz. With the final chambers that are 11.75" x 11.75" x 11" and using copper tubing for the coil, the resonator Q is limited to about 1070/1500/2150/2600/3000 for 3.5/7/14/21/28 MHz. [2] [3] Reference [3] provides an equation for maximum unloaded Q as = 50 * volume$^{1/3}$ * f ^{½} (volume is in inches-cubed and f is frequency in MHz). This is for copper coils and assumes the coil diameter is about 50% of the chamber diameter and that the coil length is 1x to 4x the coil diameter. Additional factors will further limit Q, so achieving a Q close to 2000 at 14 MHz requires minimizing all significant losses. Reference [3] included experimental results for helical filter chambers up to about 230 cubic inches and reference [2] refers to work with chambers up to about 400 cubic inches. The square chambers used in this work have a volume of 1518 cubic inches.

The value and Q of the coil or helix are also significant factors. An online tool by ON4AA is convenient for calculating inductor value and Q. [4] Given a coil of 3/8 inch copper tubing with a diameter of 6.5" and 9.5 turns with a length of 7 inches, the inductance of the coil is about 10 uH and the Q of a copper coil (not including a finite chamber size) is about 3900 at 14 MHz. By comparison, the use of an aluminum tubing coil would lower the Q (not including a finite chamber size) to 3000 at 14 MHz, so using copper for the coil is important.

The chamber material is another key question. Copper is well known to be a better conductor than aluminum. Copper has a DC resistivity of 1.68×10^{-8} ρ (Ω•m) at 20 °C and aluminum has a DC resistivity of 2.82×10^{-8} ρ (Ω•m) at 20 °C (the units are in m^2 / m or square meters for the conductor's cross section divided by the meters for the conductor's length and the units then are simply in ohms x meters). But at 10 MHz, aluminum has a skin effect depth of 25.9 um while copper has a skin effect depth of 20.6 um. The deeper RF skin effect of aluminum partially mitigates its higher DC resistivity compared to copper. This can be seen directly in equations for skin effect where the skin effect is inversely proportional to the square root of the DC resistivity (the higher resistivity of aluminum "pushes" RF current deeper into a conductor than for copper but this then partially offsets the higher DC resistance of aluminum when carrying RF currents). The resistivity divided by the skin effect depth is $8.15\mathrm{x}10^{-6}$ ρ (Ω•m)/um at 20 °C and $10.815\mathrm{x}10^{-6}$ ρ (Ω•m)/um for copper and aluminum respectively or a ratio of 0.75. So the resistivity of copper for RF is about 75% the resistivity of aluminum for RF. However, a 1 foot by 4 feet by 0.04" sheet of aluminum costs about $35 retail while a similar sheet of copper cost over $200 (as of 2021), so using aluminum sheeting for the chamber is much preferred although there is expected to be some impact on Q. Also, aluminum weighs only 30 percent of copper. Copper clad aluminum sheets might be a good option for performance approaching pure copper sheets with lower costs than pure copper, but availability appears limited in the USA, and mechanical properties may be a concern. The thermal coefficient of expansion of aluminum is about 30% higher than copper, so bimetal sheets may warp slightly over operating temperatures resulting in impact on the resonator's frequency. Copper foil is available that is much thinner than the 0.040 inch thick material used here and would have reasonable cost. And electrically thin copper foil would be fine electrically since the skin depth is only about 20 um for copper at 10 MHz. But the thin copper foil would not be self supporting and would need a well constructed frame for support which complicates construction.

Consideration of the relative importance of the resistivity of a copper coil compared to the resistivity of an aluminum chamber on the overall resonator Q suggests that the resistivity of the aluminum chamber is not a significant factor. The coil tubing has a circumference of about 1.17 inches and the coil is about 180 inches long, so the length divided by the surface width in about 150. The aluminum chamber has a distance of about 30 inches from the most distant point on the chamber surface to the common ground point where the coil connects to the chamber wall, but the effective surface width of the connection is on the order of the width of a side of the chamber or about 12 inches, and the distance divided by the surface width for the chamber is then about 2.5. These factors suggest that the resistivity of the coil dominates by about 60x compared to the chamber, so using material for the chamber with slightly higher resistivity than the material for the coil should have small effect on overall resonator Q. Aluminum was used for the chambers in this work with good results, but copper was used for the coils. It appears that the size of the chamber is the key limit on overall resonator Q followed by the Q of the coil, and copper is important for the coil but aluminum is fine for the chamber.

Coil forms or supports are well known to impact Q. For this design using copper tubing, ½” diameter plastic rods were selected to be used as vertical supports for the coil which itself is placed vertically inside the chamber. Two ½” rods are placed vertically resting on the bottom plate and on opposing sides of the coil and tie wrapped to the coil in 2 places (a small amount of epoxy secures the plastic rods to the bottom plates but only provides sufficient strength for normal upright positioning of the chambers). Optionally a third rod can be tie wrapped horizontally to the outside of the coil near its middle and placed at about 45 degrees in one corner to stabilize the coil on its 2 vertical supporting rods. Nylon and rexolite 1422 rods were selected for testing. Rexolite has very good RF properties [3], especially a low power dissipation factor, but rexolite is more expensive than nylon and harder to find. Rexolite 1422 has a power dissipation factor of only 0.00025 at 10 MHz while nylon or Polyamide 6 has a dissipation factor of 0.01 to 0.06. As shown later in measurements, the nylon rods significantly degraded Q and rexolite is needed for the supporting rods for the coil to achieve very high Q. The use of rexolite with a low power dissipation factor is also expected to be important at 1 kW power levels to avoid overheating the supporting rods and detuning of the resonators. The small tie wraps used to secure the coils to the ½” vertical rods were nylon, but only a total of 4 were used for 20 meters and 6 were used for 40 meters. The volume of the tie wraps is very small, but it may be helpful to also eliminate nylon tie wraps with an alternative such as stainless steel ties.

Chamber Construction

To construct the resonator chamber of aluminum sheeting measuring 11 inches tall by 11.75 inches wide and deep, start with an aluminum sheet 12” x 48” of thickness 0.04” and bend the sheet into a box forming the 4 vertical sides. Sources for the aluminum sheeting can be found online [5] as well as in local metal shops and hardware stores (Use aluminum sheeting with plastic film on one side to facilitate marking it for cutting and bending). Lines are drawn ½” from the edges of both 4 feet sides which will be the edges for the ½” wide flanges at the top and bottom of the chambers. Then draw a line 1” from one short edge. Next Measure 11.75” three times and draw lines to be used to form 4 chamber sides of 11.75” starting from the 1” line. Mark 45 degree corners with ½” sides where each chamber corner flange will be formed. Use heavy tin snips to remove the 45 degree corners and to cut the 1” edge to 11” length by removing ½” at each end of the 1 inch wide area. These cuts should be made just a bit larger (order of 1/16”) than the lines to avoid conflict during the sheet metal bending process.

A small metal brake (18" is a good size) is used next to make 4 bends across the 12 inch by 48 inch sheet metal on the lines at the 1 inch line and then at 3 lines drawn with 11.75 inch spacing. See Figure 1 which shows the process after 2 bends by the brake. A large square is used to help make each bend 90 degrees. The brake's bending bar needs to be clamped into position about the thickness of the metal away from the bend point. Figure 2 shows the rough chambers after the 4 sides are bent into position. The next step is to make the seam between the 1" area and the 4th 11.75 inch side. The 1 inch area is placed on the inside of the chamber, and using masking tape to hold the seam together, an initial hole is drilled in the middle of the seam area and a screw inserted to help secure the seam in place. Prior to inserting the screws for the seam, the plastic coating should be pulled back on both sides of the seam by 1 to 2 inches so that good electrical contact is made at the seam. Stainless steel screws (#6 ½ inch sheet metal screws) are inserted every 1 inch along the seam starting at ½ inch from one end using 11 screws. Leave the remainder of the plastic coating with markings in place to guide the bending of the flanges in the next step.

Now that the rough chamber has been formed and the seam has been completed, the 8 flanges of ½" width with 4 on the top and 4 on the bottom of the chamber must be bent to 90 degrees facing the inside of the chamber. This step is complicated by the need to bend the flanges into position without disturbing the rough chamber shape. A 2 step process was used which worked OK although it is a bit awkward. In step 1, all 8 flanges were bent to 45 degrees. Two pieces of ½ to ¾ inch angle iron cut to 11.5 and 10.5 inches were used. The 11.5 inch piece of angle iron was used as a bending bar on the brake for 2 flanges on opposing sides of a first the end of the chamber and then on the other end of the chamber to bend 2 opposing flanges to 45 degrees. See Figure 3. The 11.5 inch length of angle iron allows the edges of the chamber to clear the angle iron during the bending process to 45 degrees (flat bars of sufficient thickness could also be used in this step). Then the 10.5 inch piece of angle iron is used as a bending bar to bend the remaining flanges to 45 degrees centered on the flange to clear the sides of the chamber and the edges of the previously bent flanges. A hammer and anvil and heavy flat pliers are used to help straighten and align the metal at the corners.

In a final step, a heavy bench vise is used on each flange to bend it from 45 degrees to a final 90 degrees. The 10.5 inch piece of angle iron is placed on the edge of the vise inside the chamber and the 11.5 inch piece of angle iron is placed on the outside of the chamber and with careful centering and positioning the vise is tightened while working the chamber and angle iron pieces carefully into final position. This process is awkward, so proceed with patience. Then the chamber is bent by hand to about 2/3 of the way to final position. Next a hammer is used to tap lightly along the bend moving the hammer about ½ inch per tap to help form the bend. After completing the bend to 90 degrees by hand, a hammer is used lightly again along the bend to complete forming the bend. Again a large set of flat pliers may be needed to straighten and align the corners. A better process to form the flanges is possible, but this process worked OK. Once the flanges are fully formed, the plastic covering inside the chamber should be completely removed.

The SO-239 connectors are located 1 inch from the bottom of the chamber and 3 inches from the side, and the chamber seam is placed as far away as possible from the SO-239 connector diagonally across the chamber to minimize RF ground current across the seam. The RF currents on the inside of the chamber wall flow from each point on the chamber wall spreading out over the wall to the point where the coil connects to the chamber wall near the SO-239 connector. It is important that those paths be very high quality, and placing the chamber seam opposite the SO-239 connector combined with the usage of a continuous piece of aluminum sheeting to form the 4 chamber walls addresses this issue. As noted by [2] [3] the two end plates have limited impact on tuning and performance, but should be mounted with good quality electrical connections. For these chambers, the end plates had a 5 to 10 percent impact on the resonator frequency, so they are important to include during tuning, but their seams/connections appear to be less critical for RF flow than the seams/connections of the 4 sides of the chamber. Where the signal tubing needs to pass from chamber to chamber, ½" diameter holes are drilled at 1 inch from the bottoms of the chambers and 1 inch from the sides of the chambers.

The chamber end pieces are prepared by trimming about 3/8 inch from 2 sides of a 12 inch by 12 inch piece of aluminum. The bottom plates are attached with 5 screws per flange plus an added screw next to the SO-239 connector. The top plates are attached with only 3 screws per side. A circle of eight ¾" diameter holes are drilled in the center of the bottom and top plates for airflow and aligned with the blades of the cooling fans, and mounting holes for a fan are drilled in the top plates.

The following list of tools was used during chamber and coil construction:

- Sheet metal brake (18" Ironton from Northern Tools)
- Heavy tin snips
- Heavy bench vise
- 2 feet long 6 inch diameter PVC pipe section
- 7/64" carbide drill bit to drill holes for sheet metal screws
- Drill bit set – step drill bit up to 1"
- 3' of ½" steel angle iron cut to 11.5" and 10.5" pieces
- NanoVNA & laptop
- Misc shop tools – hand drill or drill press – hammer – punch – screwdrivers – heavy flat pliers

The following list of materials was used to construct each chamber and coil (includes parts for 3 chamber filters detailed in a 2nd paper)

- Sheet of Aluminum 1' x 4' x 0.04" https://www.onlinemetals.com/ $34.46
- 2 sheets of Aluminum 1' x 1' x 0.04" 2x $11.08
- 20-feet coil of 3/8 inch soft copper tubing for 20 meters per chamber – Lowes – $27.48
- 100-feet coil of ¼ inch soft copper tubing for 3 chambers for 40 meters
- 4-feet ½" rexolite rods –https://www.polymerplastics.com/rexolite-high-performance-plastic.shtml $27 (enough for 2 or 3 chambers)
- Fan 3196-FN-SX08-16-ND - Digikey $6.30
- About 75 SS #6 x ½" sheet metal screws – LightningStainless on Ebay $5
- SO-239 connector - $5
- 15 pF 15kV 35kVAR – UR5LL $7 each (3 used for filter construction for loose coupling for 20 meters and 6 used for 40 meters)
- 4 large rubber feet – 1.25" tall - $12 (used for filter construction)
- T200-6 toroid core - $6 (2 used for CW filter construction)
- 150 pF, 3.5kV, 6KVAR RF doorknob capacitors (4 used for 20 meters phone filter construction) UR5LL $4 each or 4x 330 pF capacitors used for 40 meters phone filter construction
- Misc – #12 copper wire – ¼" copper tubing

Coil Construction

A 6” diameter by 2 feet PVC pipe purchased at Home Depot was used to form the 3/8”or ¼” copper tubing coils. A 3/8” hole was drilled 1 inch from one end of the PVC pipe and one end of the copper tubing inserted about ½” and then bent sharply against the PVC pipe. Twenty feet pieces of soft 3/8” refrigeration copper tubing obtained from Lowes for $27.50 each were used to wind the 20 meter coils. The PVC pipe was placed vertically on the floor, and slowly turned as the copper tubing was slowly pressed/pulled into place. The coil was formed by unwinding the tubing supply about 1 foot ahead of the winding point and slowly pressing and pulling the tubing against the PVC pipe several inches at a time. The tubing will spring back slightly after each press/pull, so pull it back snug against the PVC pipe over the entire length with each new press/pull on the tubing.

The key to achieving a consistent smooth coil is to only slightly unwind the supply a bit at a time and to press/pull the tubing onto the form in the same winding direction as the supply. After carefully unwinding about a 6 inch segment, use one hand on the top end of the PVC pipe to tighten the coil while pressing/pulling the copper tubing into place against the form with the other hand. See Figure 5. It is preferable to wind the coil with turns a bit closer than the final target than more widely spaced than the final target, because it is relatively easy to pull the turns to a wider spacing.

When the winding is completed and after wiggling the starting end of the copper tubing out of the hole where it was inserted, the coil can easily be slipped off of the PVC pipe form. And minor corrections can be made to the coil after removal from the PVC pipe to achieve uniform spacing. To elongate the overall coil, you can take one end of the coil in each hand and pull on the coil overall which spreads the change in length overall the coil quite well. Compression can also be performed, but may be more difficult to achieve. The coil holds it form quite well, but by tie wrapping it to two vertical ½” diameter rexolite rods on the first and sixth turns, the spacing can be fine tuned and the coil securely mounted in the aluminum chamber. See Figure 6. The coils formed with ¼ copper tubing will be less rigid than the coils formed with 3/8 inch copper tubing and needs more support points with tie wraps on the rexolite rods.

Resonator Characterization and Measurements

For resonator characterization tests and measurements for the 20 meters coil, the coil bottom end was not connected to the chamber wall ground as is usually the case for building filters. Instead the coil end near the bottom end of the chamber was connected to a short piece of flexible copper braid which was connected directly to the SO-239 connector center conductor. The top end or hot end of the coil is unconnected as is consistent with helical resonators. This direct coupling arrangement results in a maximum depth notch filter with the only components involved under test being the chamber and the coil, and it is advantageous to indirectly measure unloaded resonator Q and to determine key properties of the resonator.

In addition to the SO-239 connector, a short piece of coax with a PL-239 plug was stripped on the other end a few inches from the PL-239 plug and it was connected to the SO-239 connector with the coax going through a small hole in the chamber wall. During resonator characterization, S1 of the NanoVNA was connected to either the PL-239 plug or to the SO-239 connector (with any necessary adaptor), and S2 was connected to the other connector. This arrangement was made to minimize any common inductance or coax length in the S1 and S2 paths which could affect the measurement and also reduce the measured notch depth and measured Q.

Figure 7 shows the results of the NanoVNA measurements for the case of two ½” diameter nylon support rods for the coil. The coil had about 9.5 turns with a length of about 7 inches and a diameter of about 6.5 inches made of 3/8 inch copper tubing. The depth of the resonator notch is about 37 dB with two nylon support rods. Figure 8 shows the results of the NanoVNA measurements for the case of two ½” diameter rexolite 1422 support rods. The depth of the resonator notch is about 39 dB, and this shows a high Q associated with the deeper notch than with the nylon support rods. The nylon rod results show a Q of about 1400, but the rexolite 1422 rod results show a Q of about 1800 which is important to achieve excellent results. Rexolite rods are readily available online from several sources. One source supplies 4 feet of ½” rod of rexolite 1422 for $27. [6] A 4 feet length rod can be cut into six 8 inch pieces to support coils in 3 chambers for 20 meters, but for 40 meter coils slightly longer pieces of rexolite rod at about 9 inches are recommended. Coils that resonant with direct coupling at about 16.5 MHz were used to characterize performance and modeling parameters, because with loose coupling for filters using a small capacitor of 15 pF tapping the coil at a mid-point, the resonance frequency is lowered to about 14 MHz for 20 meters operation by the additional 15 pF at mid coil.

Modeling the Helical Resonator

Modeling of the resonator was performed using QUCS which is available as a free download online. Since a helical resonator is based on distributed capacitance over the coil, it is important to include the effects of distributed capacitance in the model. A good model for the distributed capacitance is achieved using lumped element modeling with QUCS by creating a model with 8 small segments of the coil as shown in Figure 9. The inductance is estimated using ON4AA’s online calculator [4] as almost 10 uH, and it is separated into 8 segments of unequal value calculated as the incremental increase in inductance going along the inductor 1/8 of the length per step. The 8 distributed capacitors are calculated as 8 equal value capacitors sufficient to reach the resonance frequency of the resonator, and the 8 equal value series resistors modeling the RF resistance of the overall resonator (dominated by the chamber size limitation and the coil Q) are calculated as the value resulting in the achieved Q and notch depth of the resonator. With this model carefully aligned to the measurements from a single helical resonator chamber, it is then possible to accurately model filters constructed of multiple helical resonator stages. Figure 10 shows the simulated helical resonator response which is well matched to the measured response for 1) frequency; 2) notch depth and resonator Q; and 3) bandwidth at 3 dB less attenuation than the peak notch attenuation.

Simulations show that the RF voltage at the end of the coil can go as high as 25 times the value at the input to the helical resonator. For 1 kW at 50 Ohms, the peak voltage is about 300 volts so 7,500 Volts is expected at the end of the helical coil, but this may be higher for SWR’s in the 2 to 3 range or up to 15,000 Volts. If any capacitance is added at the end of the coil, 25kV to 30 kV capacitors are needed to provide good margin. For loose coupling at mid-coil, 10 to 15 kV capacitors are needed. For kW operations, the kVAR rating is also important due to the high currents, and values of 15 to 30 kVAR are recommended.

For cooling, 80 mm on a side 12 VDC fans selected for quiet operation at about 20 cfm are mounted in the center of the top plate with the fins rotating over 8 holes at ¾” diameter. The fan draws cooling air over the coils which may need to dissipate up to about 25 Watts average in some cases. It is important to limit temperature changes in the coil and chamber to about 25 degrees F to minimize frequency shifts in the resonator.

Conclusion

The measured results show that helical resonator Q's approaching 2000 can be achieved for 20 meters with aluminum sheet metal chambers that are almost 12 inches per side and with large 6.5" diameter coils constructed of 3/8 inch copper tubing. The heavy coils and chambers should be useful to build extremely sharp filters for 20 meters and with higher inductance coils for 40 meters using multiple resonators. Measurements showed that the supporting rods for the coils have significant impact on Q and rexolite 1422 rods are needed to achieve good results. The aluminum chambers are readily constructed (with some patience and care) using inexpensive aluminum sheet metal and simple tools, and the coils are readily wound using inexpensive refrigeration copper tubing. A 2nd paper provides details on 3 stage USLL filters constructed with these chambers for 20 and 40 meters suitable for 1 kW CW and phone operations on the same band from the same location. Such filters are a good tool to help eliminate inter-station interference for same band operations for QSO parties and Field Day.

References:

1. "Filters for Separating Same Band Signals," Nelson Sollenberger, KA2C, NCJ, Nov-Dec 2021.
2. "Helical-Resonators Design Techniques," James R. Fisk, W1DTY, QST June, 1976.
3. "Coaxial Resonators with Helical Inner Conductor," Macalpine and Schildknecht, Proceedings of the IRE, Dec. 1959.
4. https://hamwaves.com/inductance/en/index.html#input
5. https://www.onlinemetals.com/
6. https://www.polymerplastics.com/rexolite-high-performance-plastic.shtml

Figure 1 - Bending the Chamber Sides with the Brake

Figure 2 - Chambers after Bending the Sides

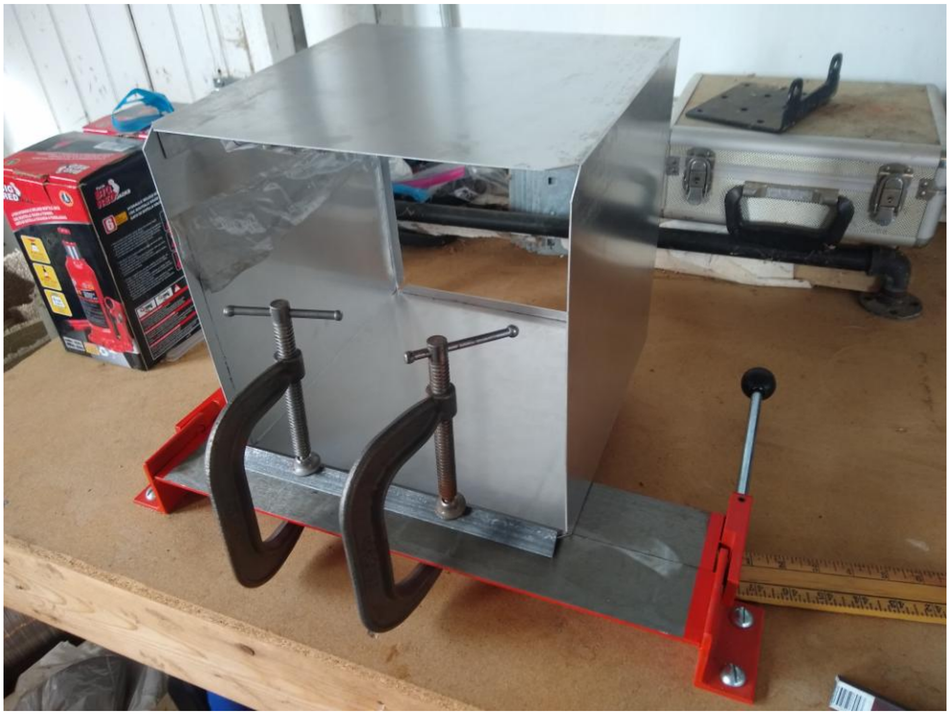

Figure 3 - Bending the Chamber Flanges to 45 Degrees on the Brake

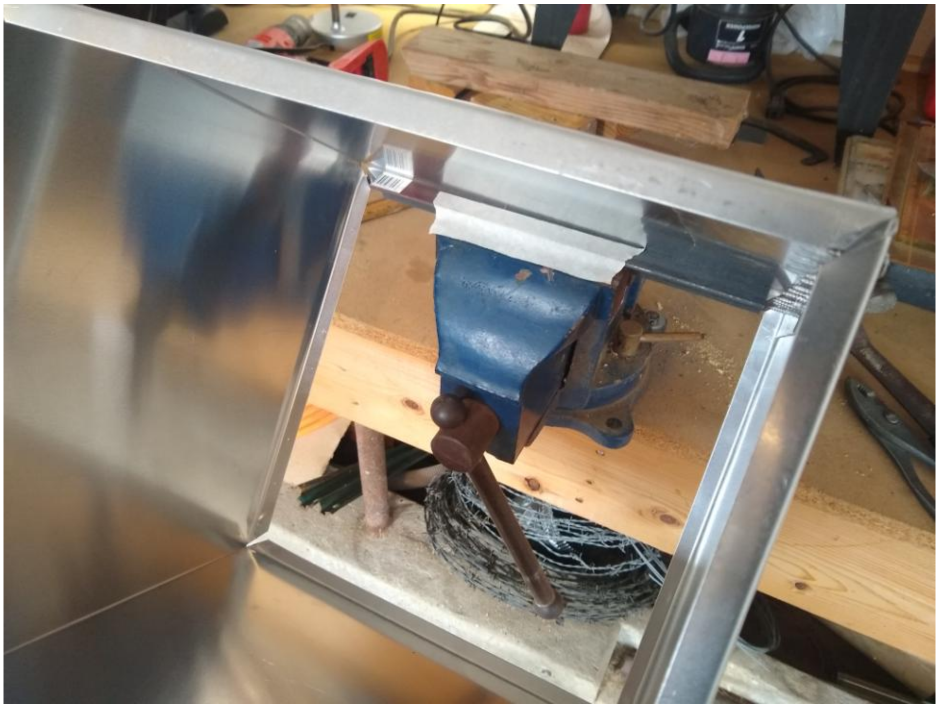

Figure 4 - Bending the Chamber Flanges to 90 Degrees on the Vise

Figure 5 - Winding the 6.5 inch Diameter Coils

Figure 6 - A Coil Mounted in a Chamber on Rexolite Rods

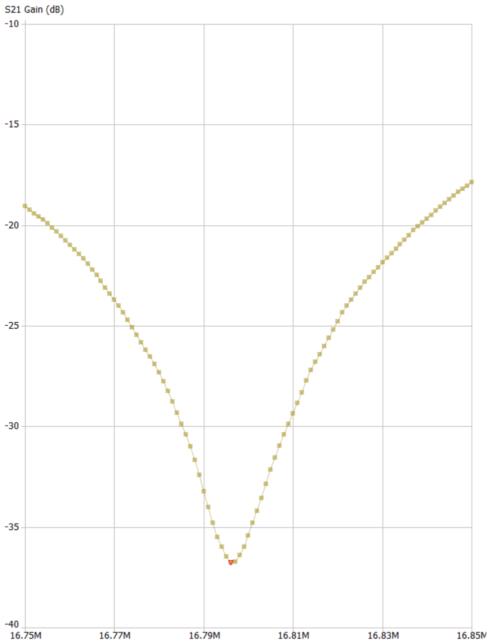

Figure 7 - Two Nylon Support Rods

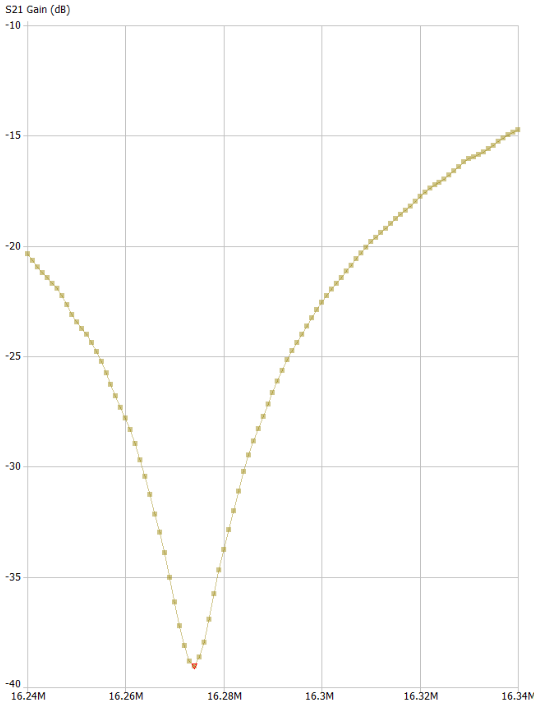

Figure 8 - 2 Rexolite Support Rods

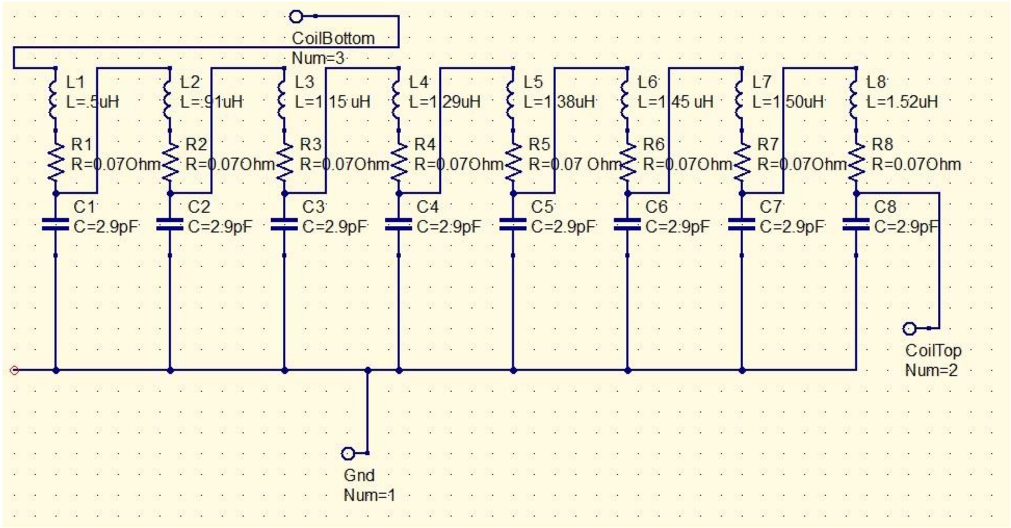

Figure 9 - Resonator Model Using 8 Segments in QUCS

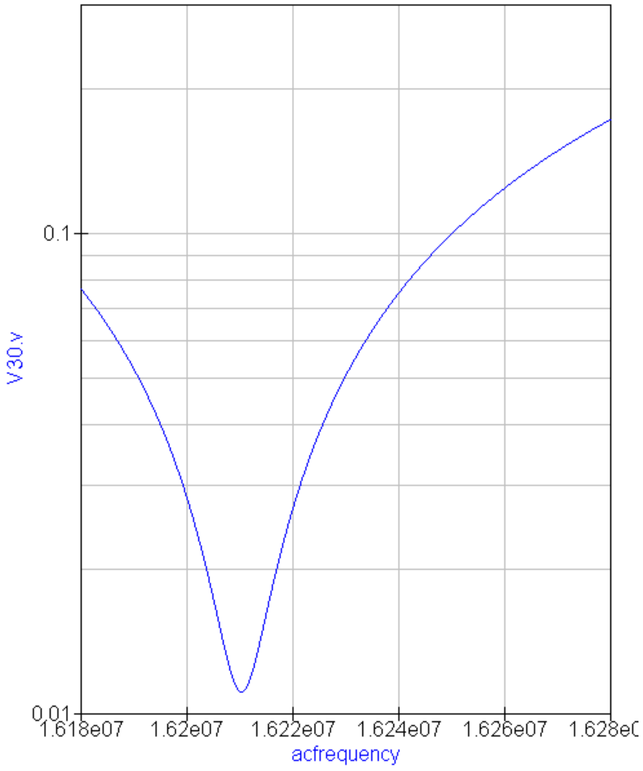

Figure 10 - Resonator Simulated Response using QUCS