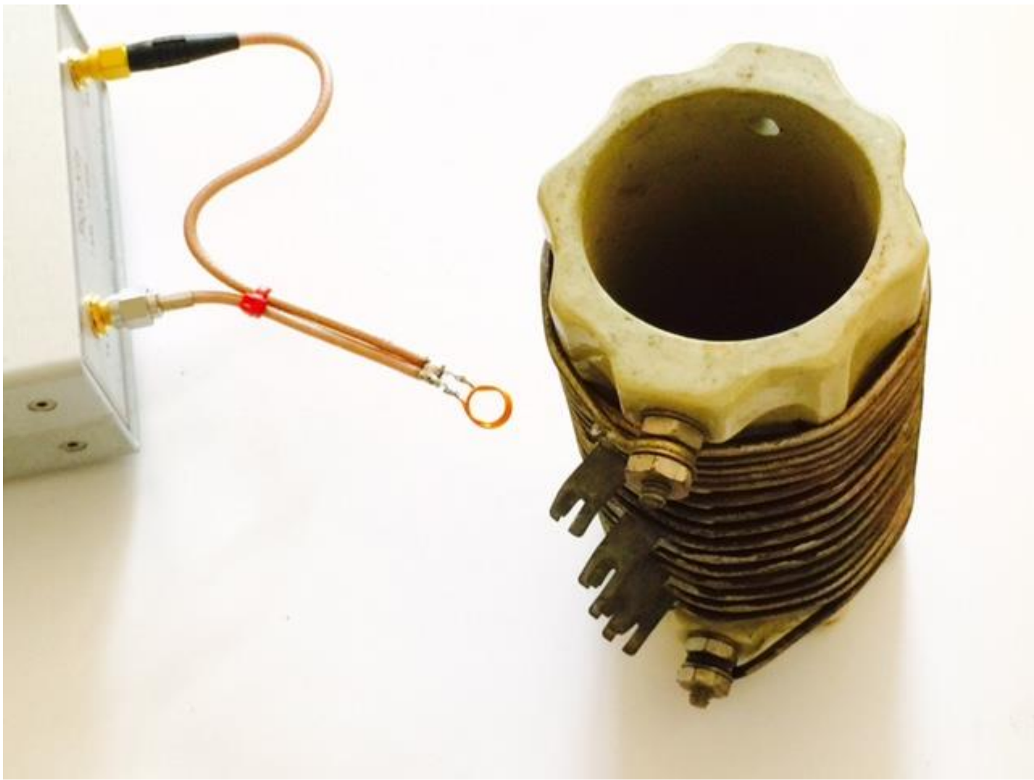
How to measure the resonance frequency of an air coil and a reliable Q measurement with the VNWA.

Preface:
Measurement of an air coil with a VNWA, or any other VNA, is far from easy and many relatively unknown factors creates wrong results.
S11 measurements can be performed, taking into account compensation for the delay in adaptors added after the test lead has been calibrated e.g. at the male SMA connector ending the test cable. Such an adaptor must be added for soldering wires to the adaptor, connecting the coil to be measured. The delay introduced are offset by using the Ext Port1 Delay function in the VNWA software and a delay is trimmed such that when measuring phase before coil wires soldered to the adaptor is 0 degree, with a resolution per division of 1 degree. Then we obtain that the parallel resonance frequency is not lowered by any shunt capacitance from the adaptor used. The short and load calibration is not influenced by any degree of importance. However the wires connected to the coil introduces shunt capacitance to the coil and lowers the self-resonance frequency considerable. For the coil shown in this report from 28.4MHz down to 25MHz.

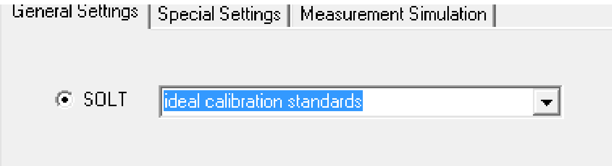
The only trustworthy method to measure the self-resonance frequency of a coil I have found, is to pick some microscopic energy from the VNWA and detect that energy transfer as described below.

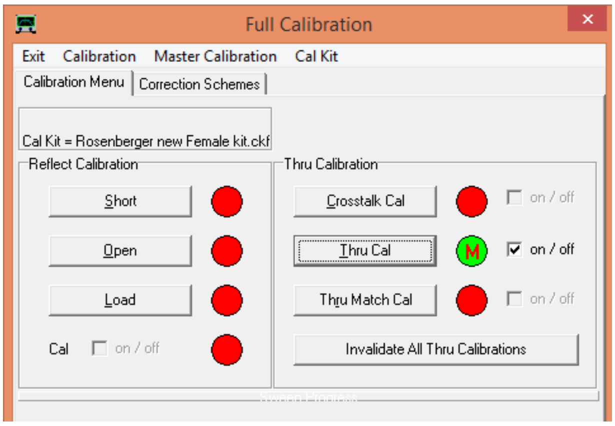
Make a test device as on the picture below, where a coil of e.g. 2 windings is inserted in the path from TX to RX port, with the screen soldered together and the coil connecting the two inner conductors. Energy can be absorbed in a distance where the pickup coil is not introducing capacitive detuning of the coil under test. Keep the coax cables at a right angle to the coil as shown. Do not move around the VNWA and the pickup coil but only the coil under test and keep the coil vertical at all times when measured, as if laid down in it side the self-resonance frequency drops due to capacitive influence from the isolation material (e.g. a plexiglas plate or a ceramic tile) it is placed upon. The coil must be kept far away from metallic surfaces such as a metal workbench or the like.



Calibration of the S21 coil setup.
The great benefit of using a S21 measurement method is that the influence from the pickup coil is calibrated away and for all frequencies the dB trace is completely flat at 0dB
Chose the ideal calibration standard in calibration setting menu where S21 delay is set to 0 and then perform a Thru calibration only**.**
REMEMBER TO REMOVE THE COIL DURING CALIBRATION

Select e.g. 1000 points and 20mS per point during calibration and a frequency span sensible for the coil under tested, in this example 1 to 50MHz. During measurement you can reduce the time per point for a faster sweep.

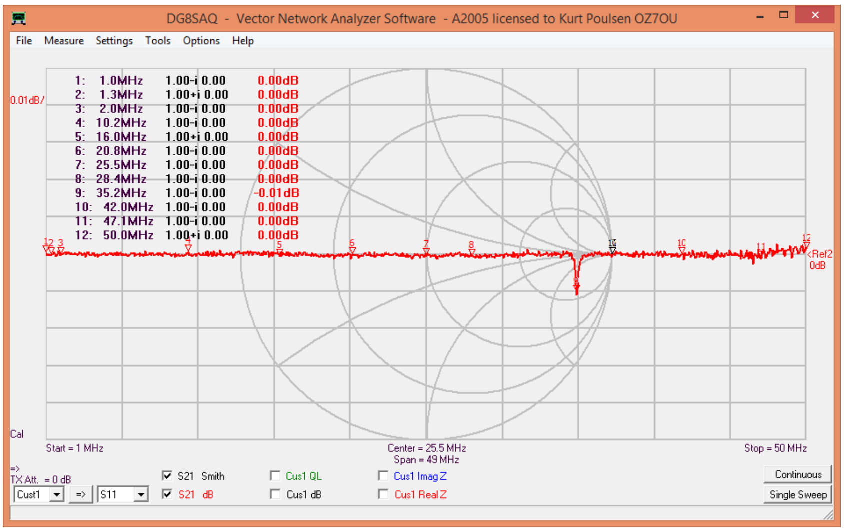




For the display of the S21 trace choose dB and **<u>0.01dB per division</u>**

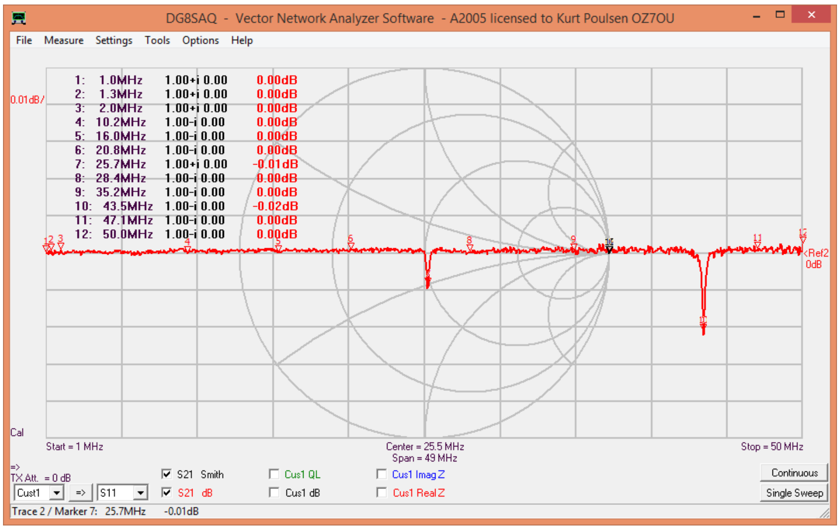
The other trace settings shown are not relevant for this test and the markers are just randomly thrown across the frequency range initially ☺

As seen a clear dip apear at marker 8 by 28.4MHz. Moving the coil does not change the dip or inverting the coil neither. The calibration might drift so just recalibration frequently might be needed, but remember to change back to e.g. 20mS per point during calibration.

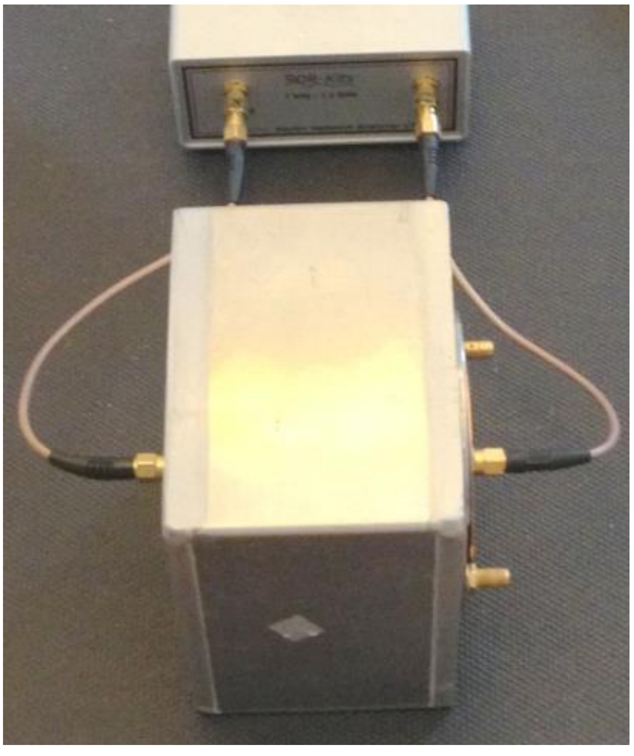


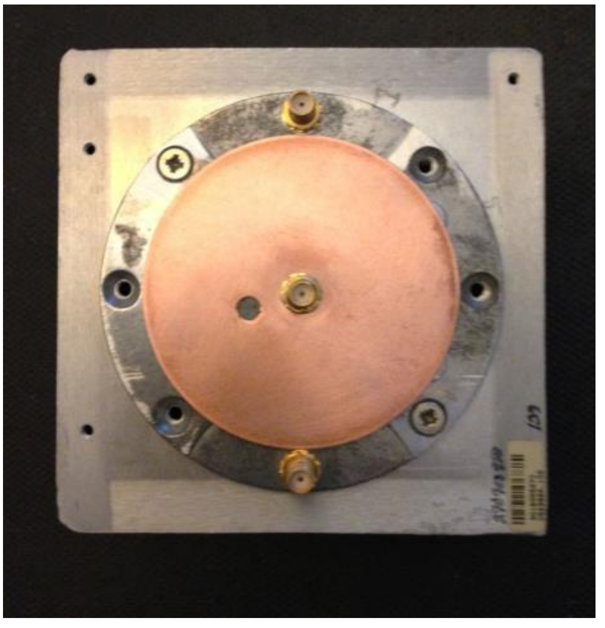
Then what about measuring the coil as S11 reflection ??

For that porpose is chosen another coil with even higher inductance and further problem as having more than one self-resonance at 25.7MHz and 43.5MHz.



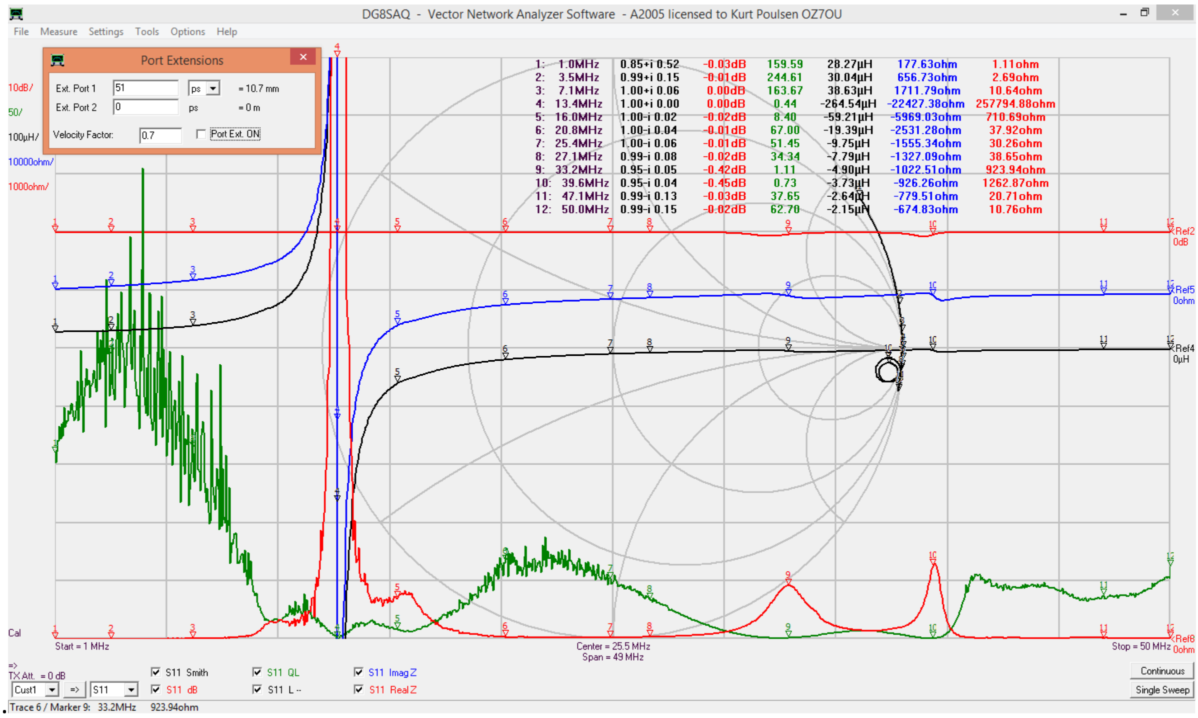
In general measuring the S11 parameters with any VNA of an air coil is pretty hopeless in free air. The parrallel resonance changes by just the slightests movement of the VNWA and in particular when the USB cable is moved around. The Q values likewise changes for every change in how the USB cable is placed. The Q curve is noisy as the measured coil is an excellent antenna and can pick up shortwave signals and the room noise from Switchmode controlled LED light and so on. Even the PC LCD screen and the computer circuitry contributes.
Nothing is really to trust and the reason is the following:
Consider the VNWA as a transmitter brougt into the center of a weird dipole antenna where the one side is the USB cable and your computer which further is capacitively coupled throught the AC to DC power supply which is connected to the AC mains supply (you may run battery operated but does not help much), and the other side of the weird antenna is the coil under test incl. the cable from the TX port to the adaptor to which the wires to the coil is connected/soldered. There is mutual coupling between the coil and the rest of your setup both eletromagnetic and electrostatic (capacitive), and the coil as such is an excellent antenna.
There is only possible cure is to bring the coil into a screned chamber. For small coil like for lowpassfilters, in the 30MHz range upwards, I have made a chamber about 10x10x10cm (from an old 900MHz stepper moter tuned bandpassfilter) with a number of female female adaptor fittted so I can SOL calibrate on the inside of the chamber. On the top lid I have three female female adaptors, where the center adaptor is for fitting the coil under S11 measurement (the remaining two for others experiments) and the single on the other side is for when I want to measure S21 in a screened environment.





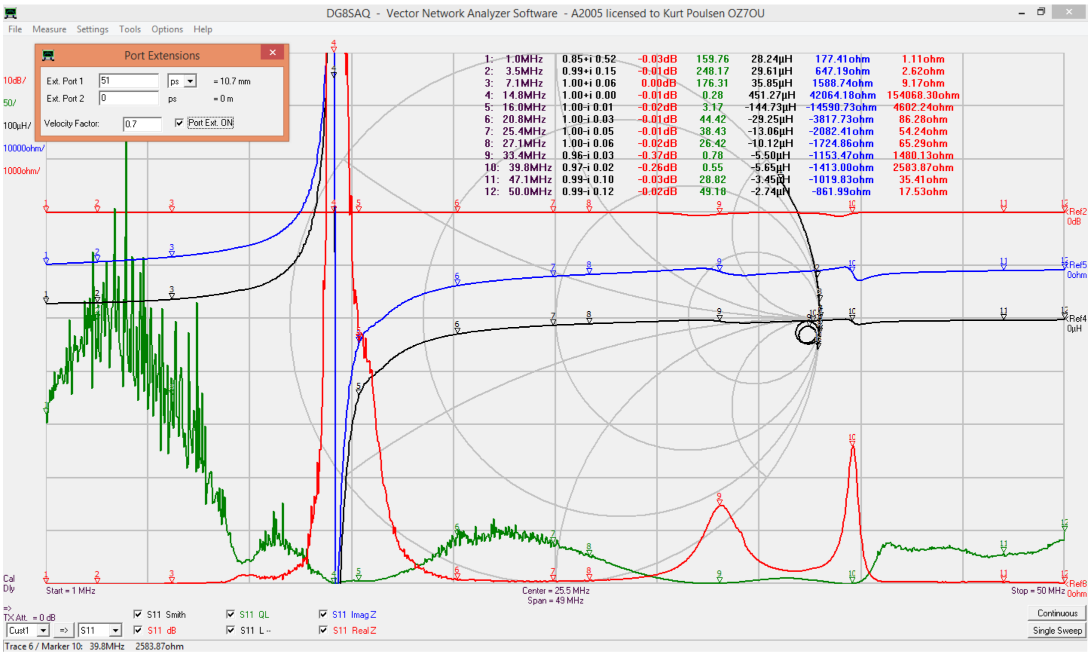
The only important detail is that the Ext. Port delay must be used to compensate for male SMA adaptor used for mounting the coil under test, and as mentioned before by measuring the phase before the coil is soldered to the adaptor. Keep the center conductor wire very short. I use a SMA male adaptor fitted with 5mm semirigid cable and the center conductor 3 mm longer than the screen.

So for a big coil as on the picture above, you may go to the shop where you purchase paint and get the biggest paint can you can get and mount a SMA type female female bulkhead adaptor in the center of the lid.
Ensure the coil is supported so it is vertical in the center of the big paint can.
The coils self resonance is 25.7MHz with a second parasitic resonance at 43.5MHz.
For theVNWA measurements a small SMA flange adaptor was used to which short wires are soldered directly. The length of this adaptor from the calibrationplane (recessed 2mm) to the rearside is 10.6mm and provides a one way delay of 10.6x4.83ps = 51ps to be entered in the VNWA Ext port 1 delay field.



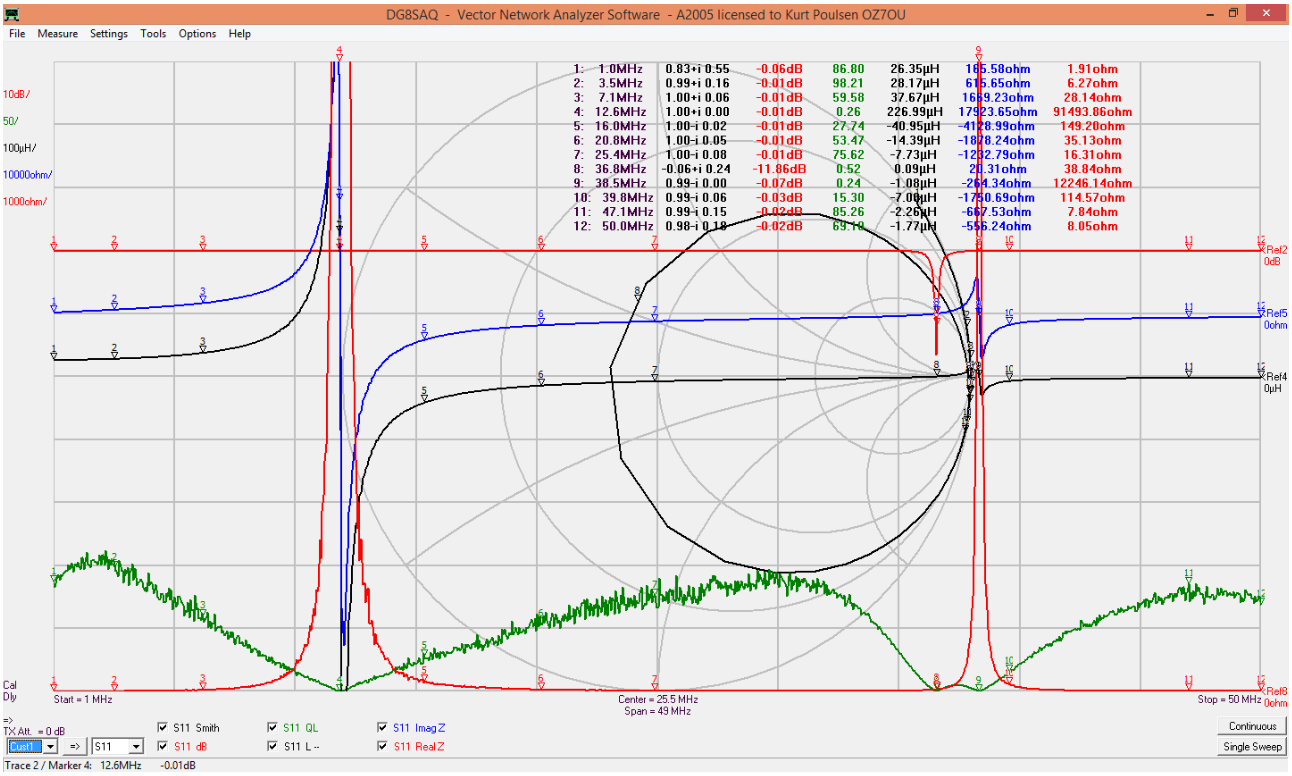
Above is measured the coil in open air without compensation for the added SMA flage adaptor which has a delay of 51ps.
The parralel resonace lowered to 13.4MHz due to the capacitance for the wires conneting the SMA flange adaptor with the coil and the capacitance in the SMA Flange adaptor. Q curve quite noisy.
Inductance at 11MHz 28.27uH and raising with frequency e.g. 38.63uH at 7.1MHz due to the parralel capacitance.

Applying the Ext Port1 delay of 51ps raises the parrallel resonance to 14.8MHz as seen below.
Inductancce at 1MHz 28.24uH so basicly unchanged but at 7.1MHz 35.85uH some 3uH less due to the resonance frequency being higher. Q seems to peak at about 230 but very hard to judge.



So what happens if we mount the coil inside a small paint can ??

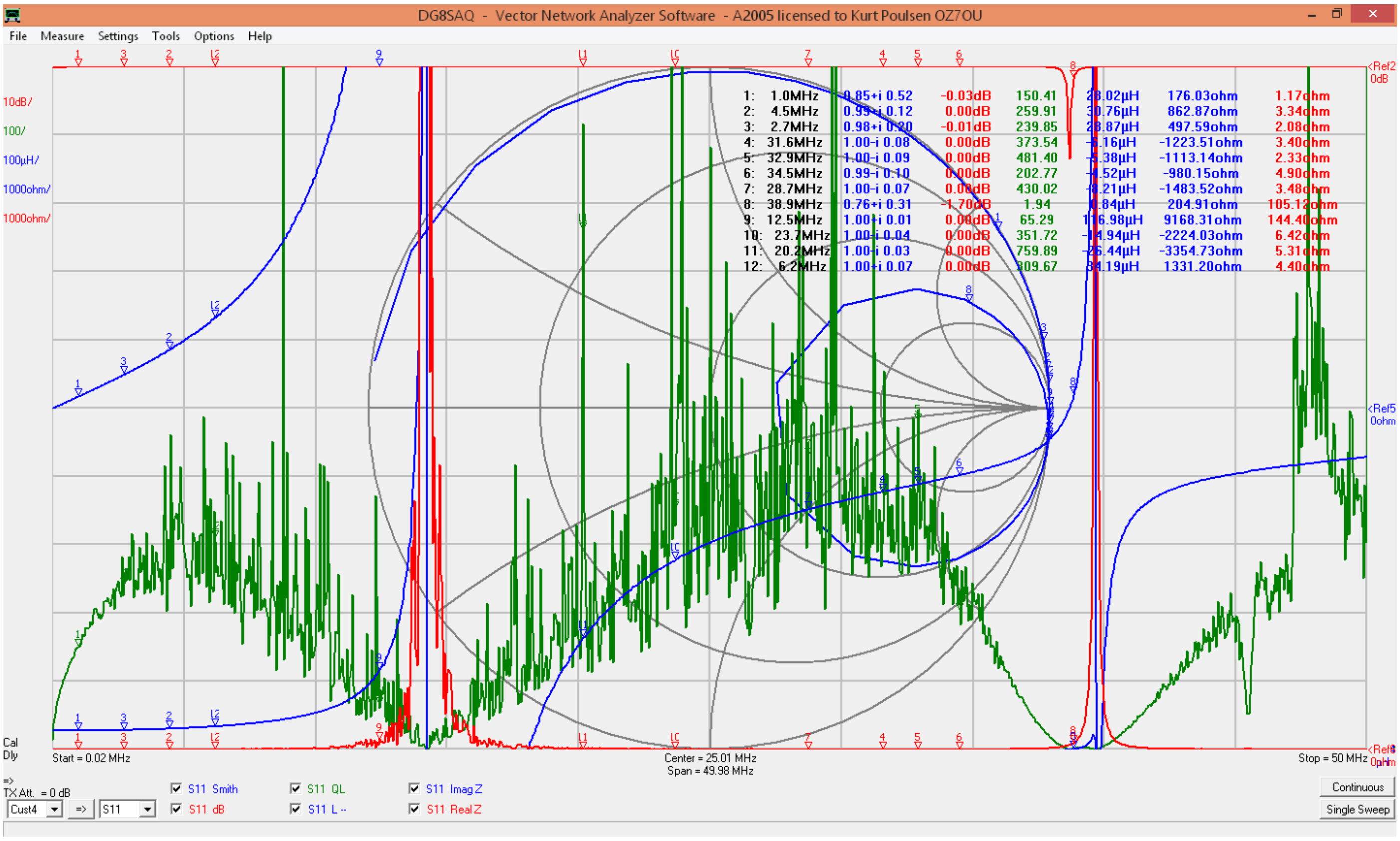
A much cleaner Q trace but also aparently a lower Q now peaking at 100 and inductance also lower



So how about a big paint can ??

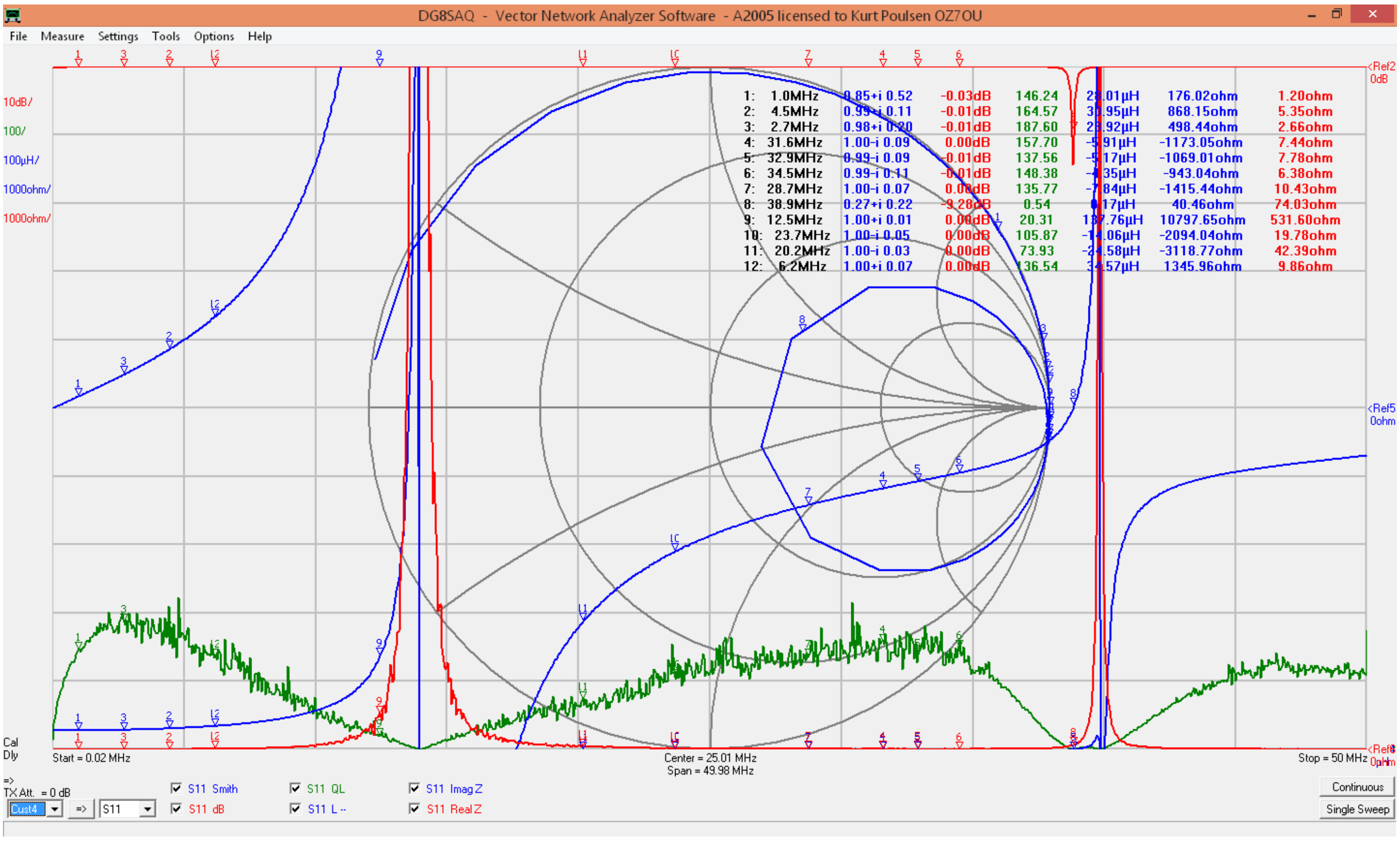
As it is big a 1 meter male male SMA testcable was used, so it could be placed on the floor.

Holly Moses, what an awfull Q trace !! Even if the coil is in the screen chamber the 2 meter long testcable creates trouble togeter with the (long) USB cable.

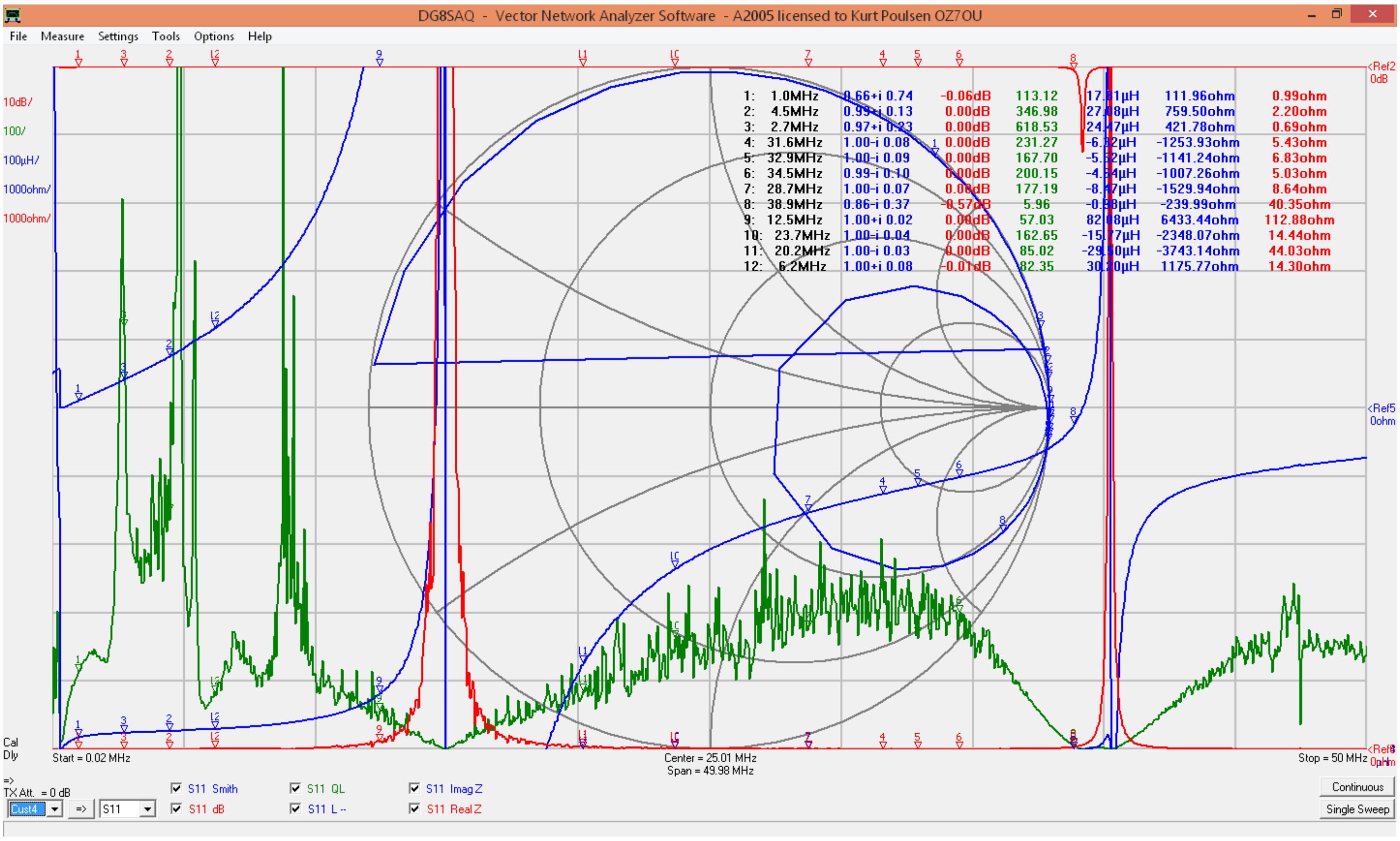


Next test is when the VNWA placed on top of the can and a very short test cable used.

Q trace not so noisy but peaking at some Q of 190 (which later will be seen is the right figure). The trace is stable form Sweep to sweep.



BUT BUT BUT, the PC power supply disconnected and awfull Q trace is seen.

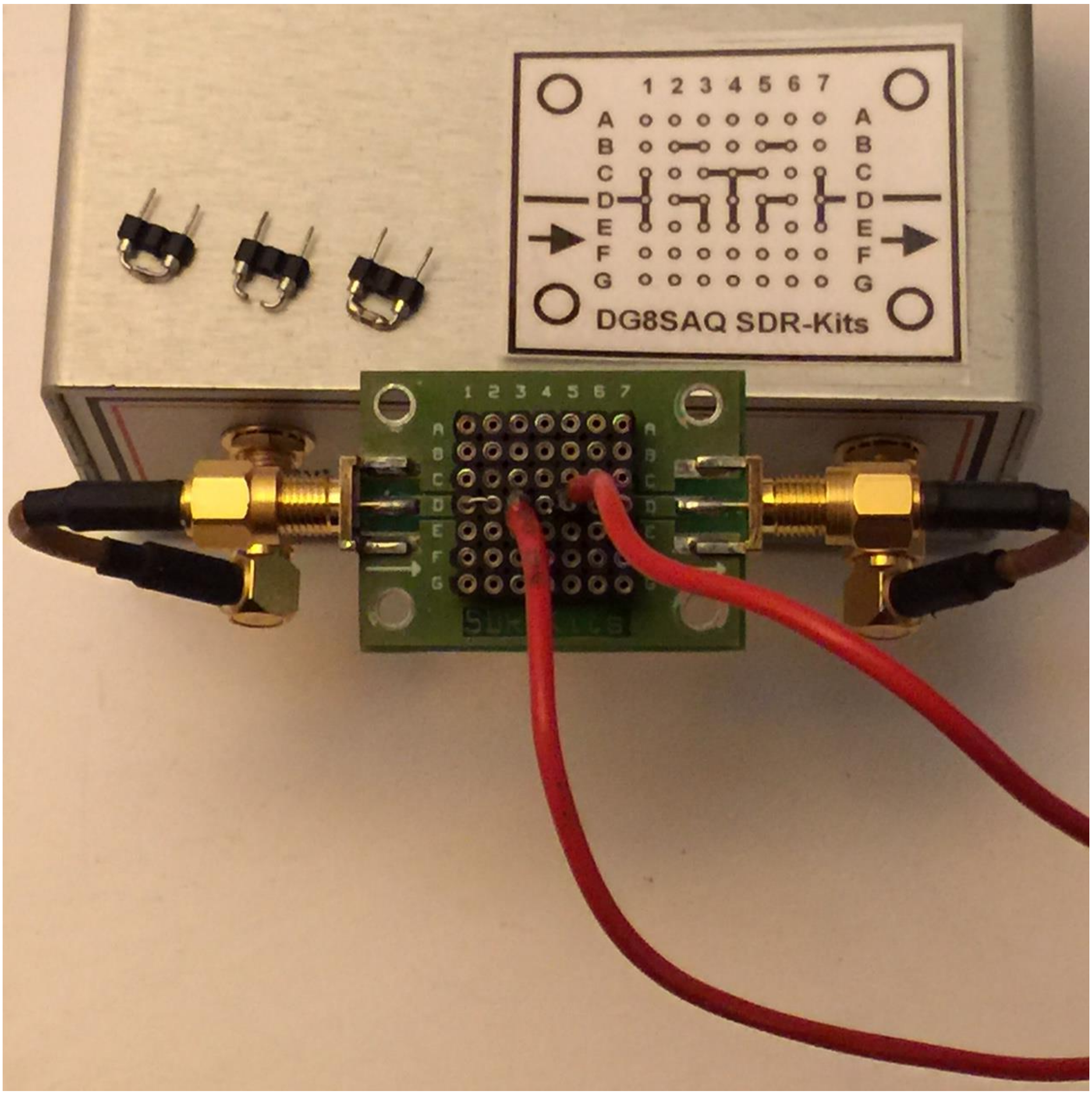


Conclusion so far:

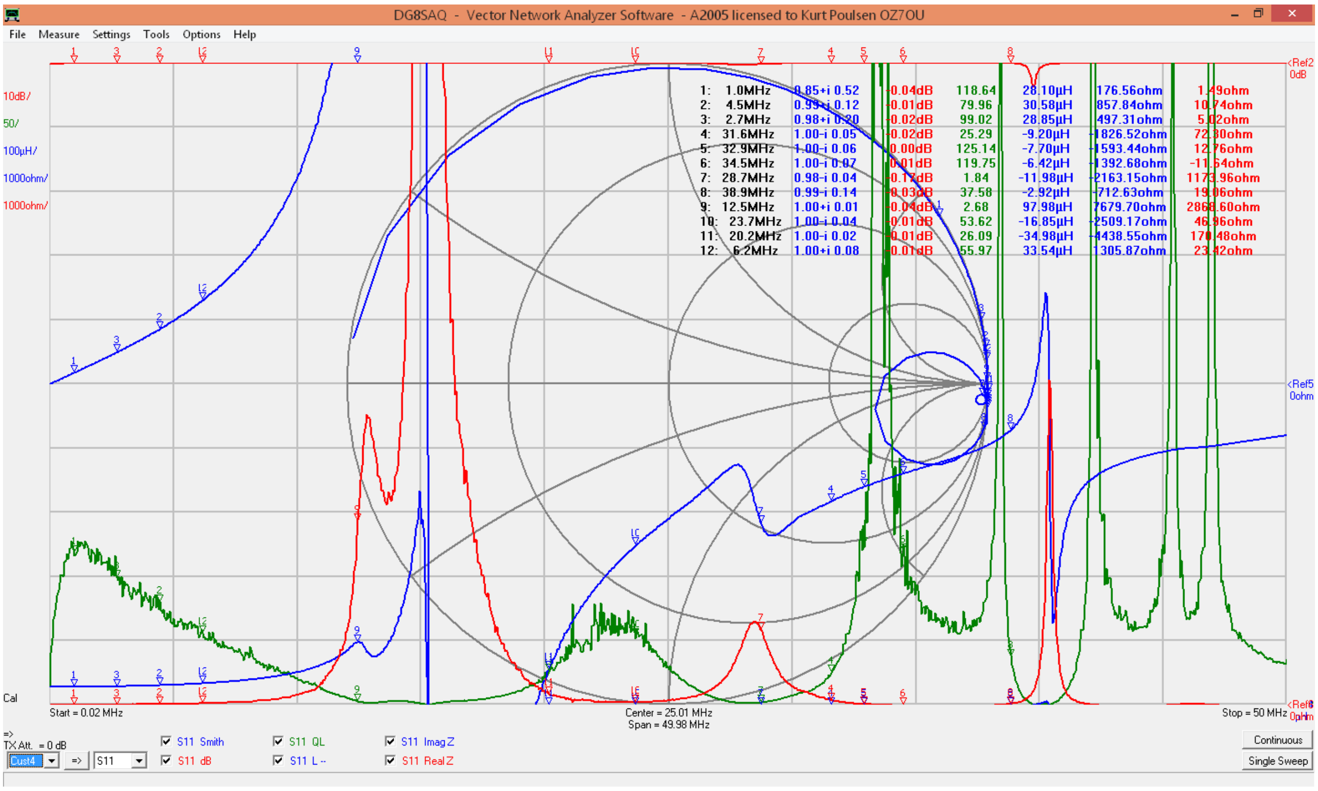
The statement in the beginning of the report is still valid. Measuring a large air coil with a VNA in open air and also in a screened environment like the paint can is impossible with any confidence for two reason. Firstly the already described coupling between wires and VNWA mainly caused by current running in cable screens inducing error voltages to the RX input port. Secondly a VNWA calibrated in the normal SOL(T) way is having a hard time when measuring impedance much away from 50 Ohm and we are dealing with resistive values 38Kohm to 193Kohm at resonance and the inductor has impedances ranging from some 150 ohm to several Kohm. That is quite imposible to measure and just the slightest error in the calibration a dramatic change in the Q value take place.

So what to do ??

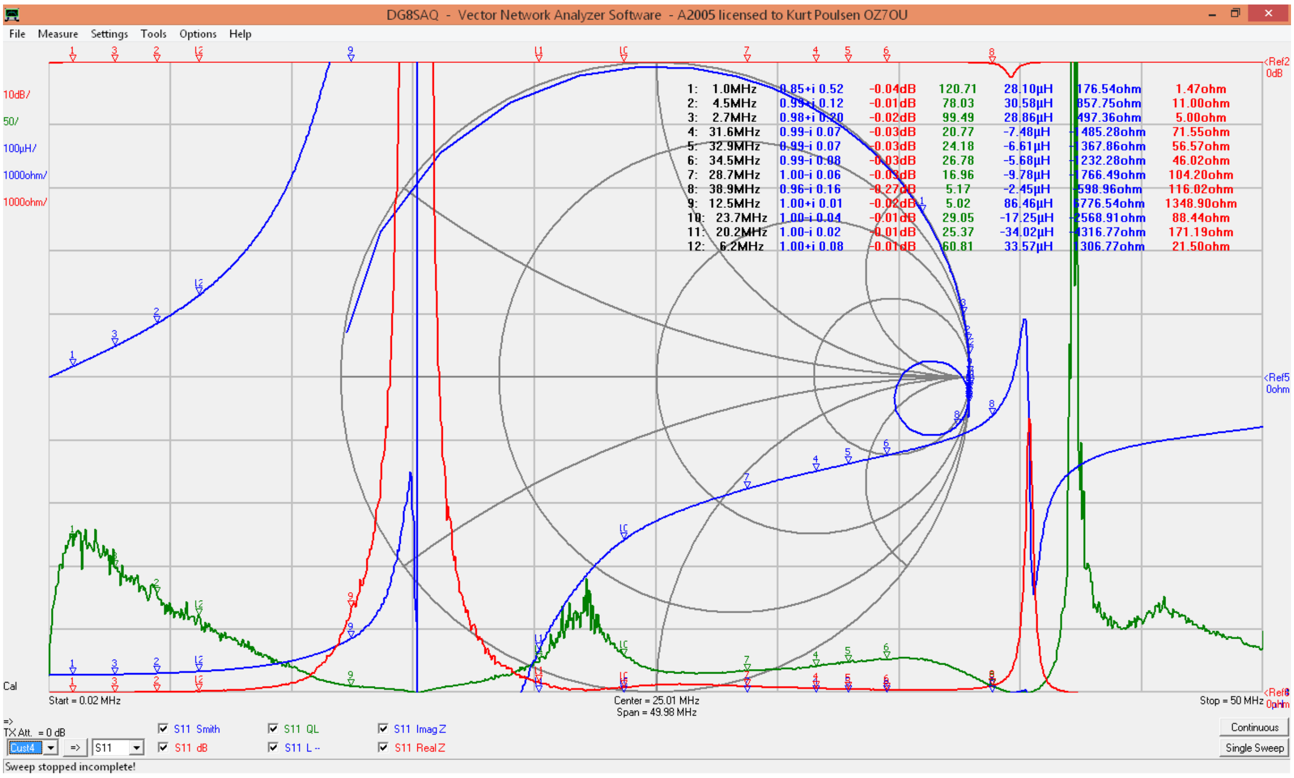
The VNWA can measure balanced when the DUT is connected in serie with the TX to RX path. Then we might get the uncontrolled circulation current in the cables better suppressed. It is actually possible to calibrate the VNWA in the traditionally SOLT way in this mode if we just limit the S21 calibration to Thru only in addition to Short , Open and Load calibration.



These homemade calibration standards placed on top of the VNWA are to the left a common Short and Thru standard, then a Open and a Load consisting of two 100ohm 0.1% SMD 805 resistors. They are just inserted where the coil leads are placed in the picture and a SOLT calibration performed.



Quite better Q trace with less noise and stable readings peaking at Q=125 but notice in below picture how the traces are much different above 10MHz just by putting a finger on the case of the VNWA. There is still coupling to the USB cable as still extremely sensitive to how the cable is placed on the table.

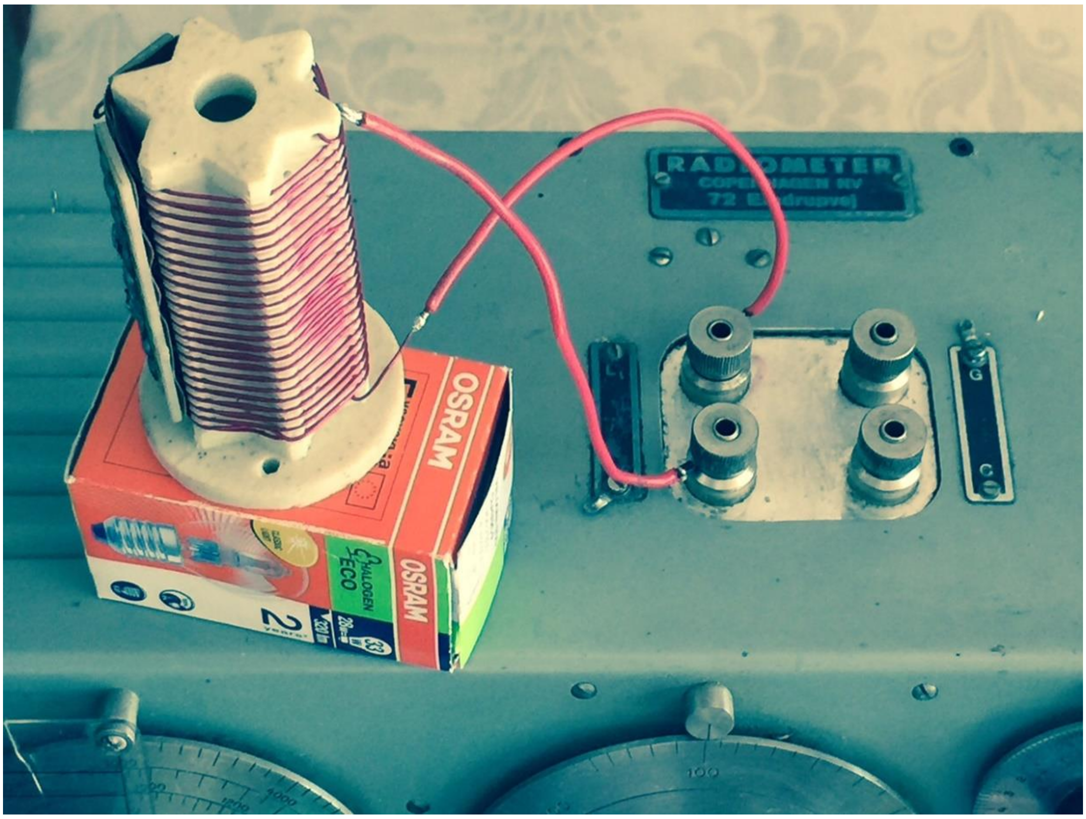


The conclusion is there is no relaible way to directly measure the Q of Coils with the VNWA in direct reflection mode, even in balanced in S21 series mode. The V method where a T adaptor used as external bridge has also been tested with negative result as only useable for lav impedances.

There is a need for a little invention as will be presented shortly, but before I want to demonstrate how an old fashion Q meter play a role together with the VNWA and how to derive all parameters which the Q meter not directly can derive because it only maesures the numeric impdance and not any phase angel.

Such a beatifull old Danish Radiometer Q meter type QM1d still does the job ☺

It has not been switched on for many years, so it was a bit slow on getting the vacuum tubes fired up and being stable, but after an hour or so, it was like in good old days. Ranging from 46KHz to 160MHz it is able to measure calibrated Q up to 625 (full scale of 250 x 2.5)



Setting the Capacitance to 500, 400, 300, 200, 150, 100, 70 and 50 pF the frequency F tuned to resonance and Q noted.
When C and F and Q are known the Coil impdance and inductance can be calculated. Likewise the equivalent series and parallel resistor at resonance can be calculated. The only “snake in the paradise” is the shunt C of the coil which is part of the coil inductance and not directly to derive. By entering the measured data into a spread sheet we can calculate the other parameter. The formula for XL seen below and for RS it is =+D2/C2 for Rp it is =+D2*C2 and for L uH it is =+D2/(PI()*2*A2)

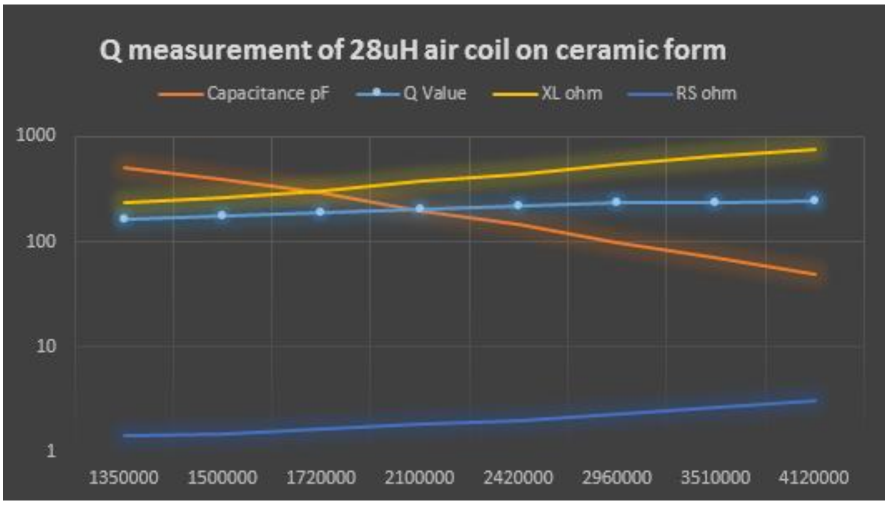
D2 =1000000000000/(PI()*2*A2*B2)

	A	B	C	D	E	F	G
1	Frequency	Capacitance pF	Q Value	XL ohm	RS ohm	Rp ohm	L uH
2	1350000	500	162	2.36E+02	1.455464	3.82E+04	2.78E-05
3	1500000	400	175	2.65E+02	1.515761	4.64E+04	2.81E-05
4	1720000	300	188	3.08E+02	1.640637	5.80E+04	2.85E-05
5	2100000	200	205	3.79E+02	1.848489	7.77E+04	2.87E-05
6	2420000	150	218	4.38E+02	2.011208	9.56E+04	2.88E-05
7	2960000	100	235	5.38E+02	2.288024	1.26E+05	2.89E-05
8	3510000	70	240	6.48E+02	2.699005	1.55E+05	2.94E-05
9	4120000	50	250	7.73E+02	3.090387	1.93E+05	2.98E-05

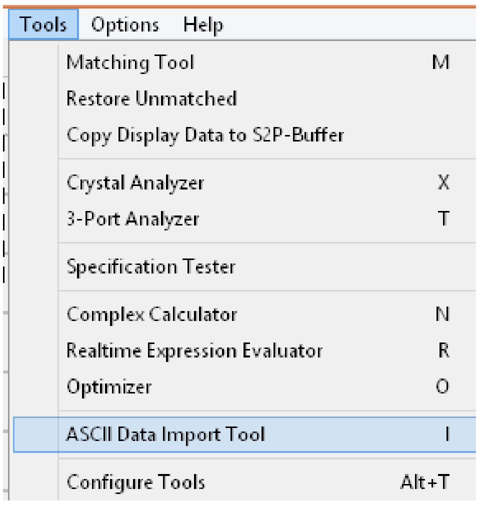
The spreadsheet is also saved in “Text (Tab delimited (*.txt)” format because we are going to import it into the VNWA software later on.

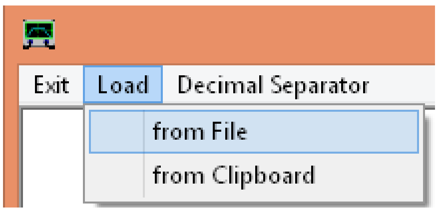
Excel Template (*.xltx)
Excel Macro-Enabled Template (*.xltm)
Excel 97-2003 Template (*.xlt)
Text (Tab delimited) (*.txt)
Unicode Text (*.txt)
XML Spreadsheet 2003 (*.xml)
Microsoft Excel 5.0/95 Workbook (*.xls)
CSV (Comma delimited) (*.csv)

A graphical presentation of the Spreadsheet calculations

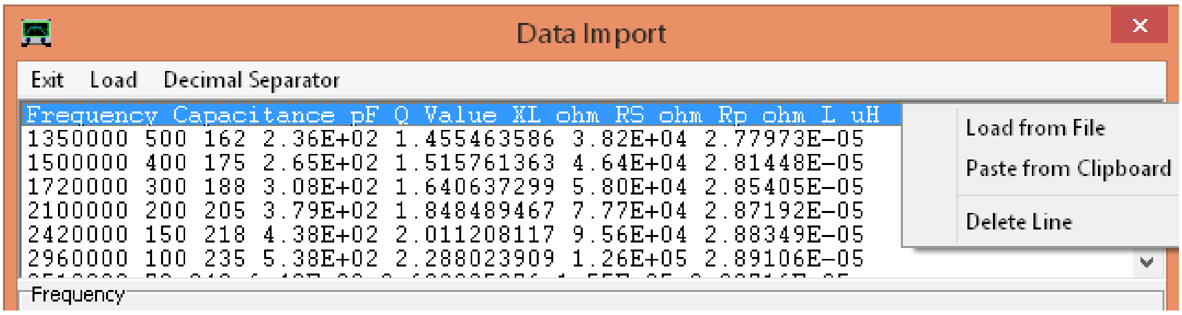


Next step is to open, in the VNWA software, the new ASCII Data Import Tool and to Load from File the saved txt spreadsheet.

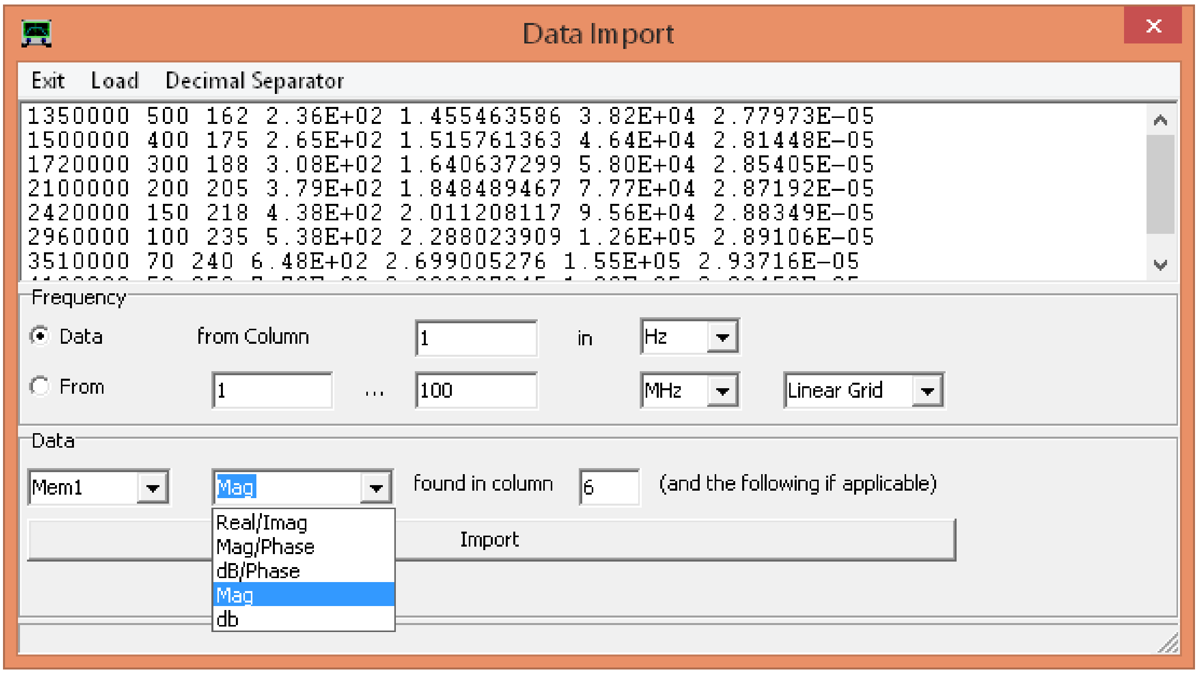




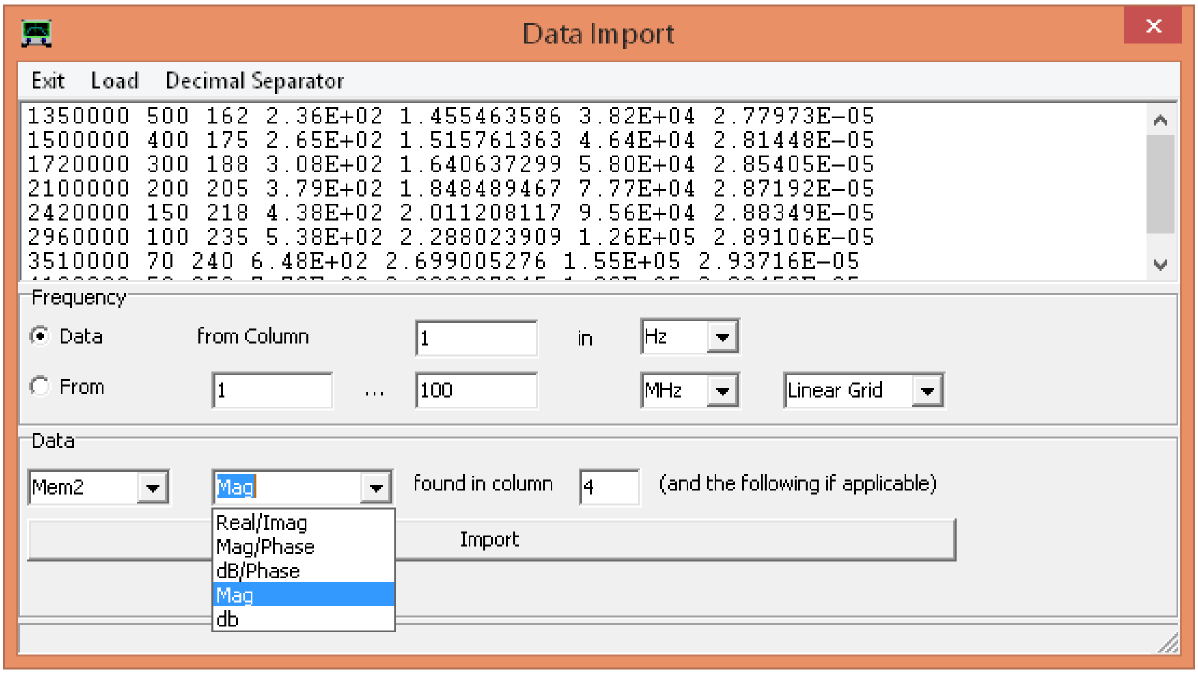
The Text line shall be deleted



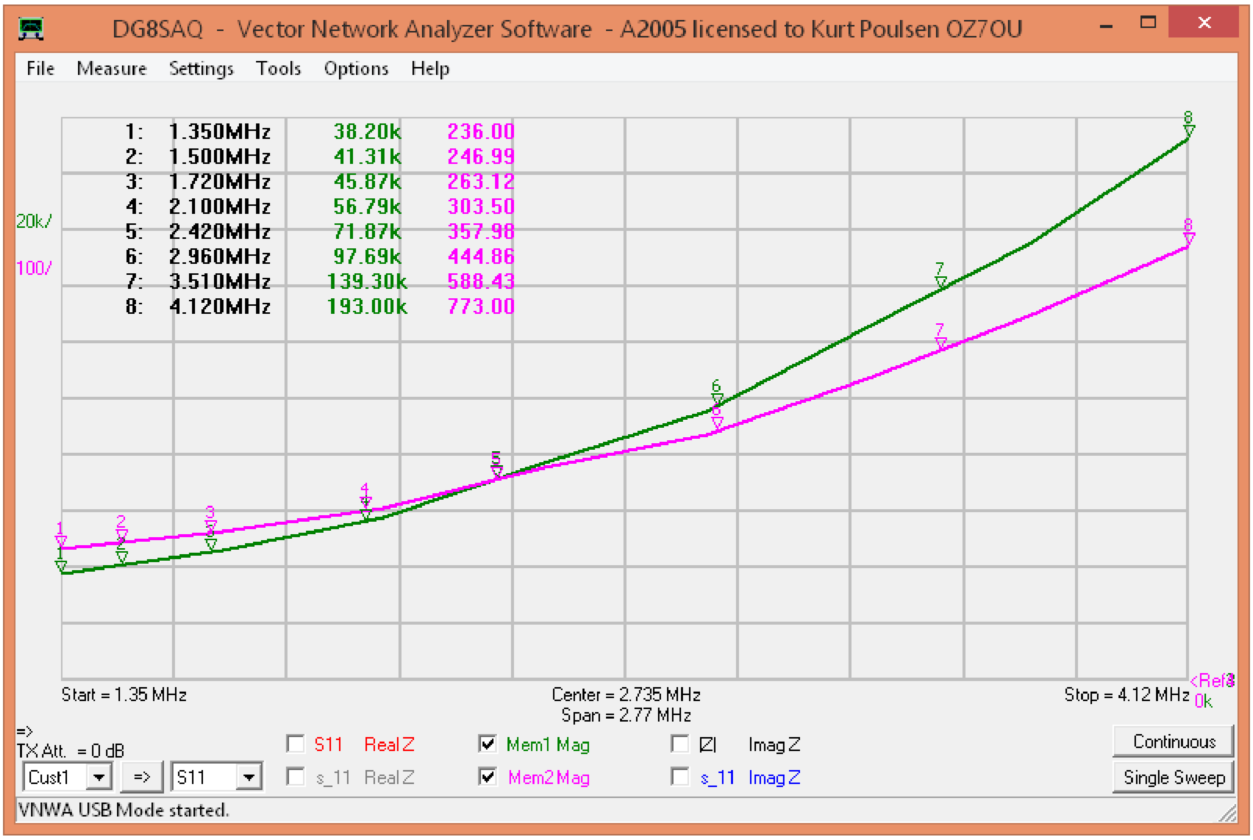
And the Frequency Data marked to be fetched from Column 1. The Rp value imported as Magnitude to Mem1 from Column 6



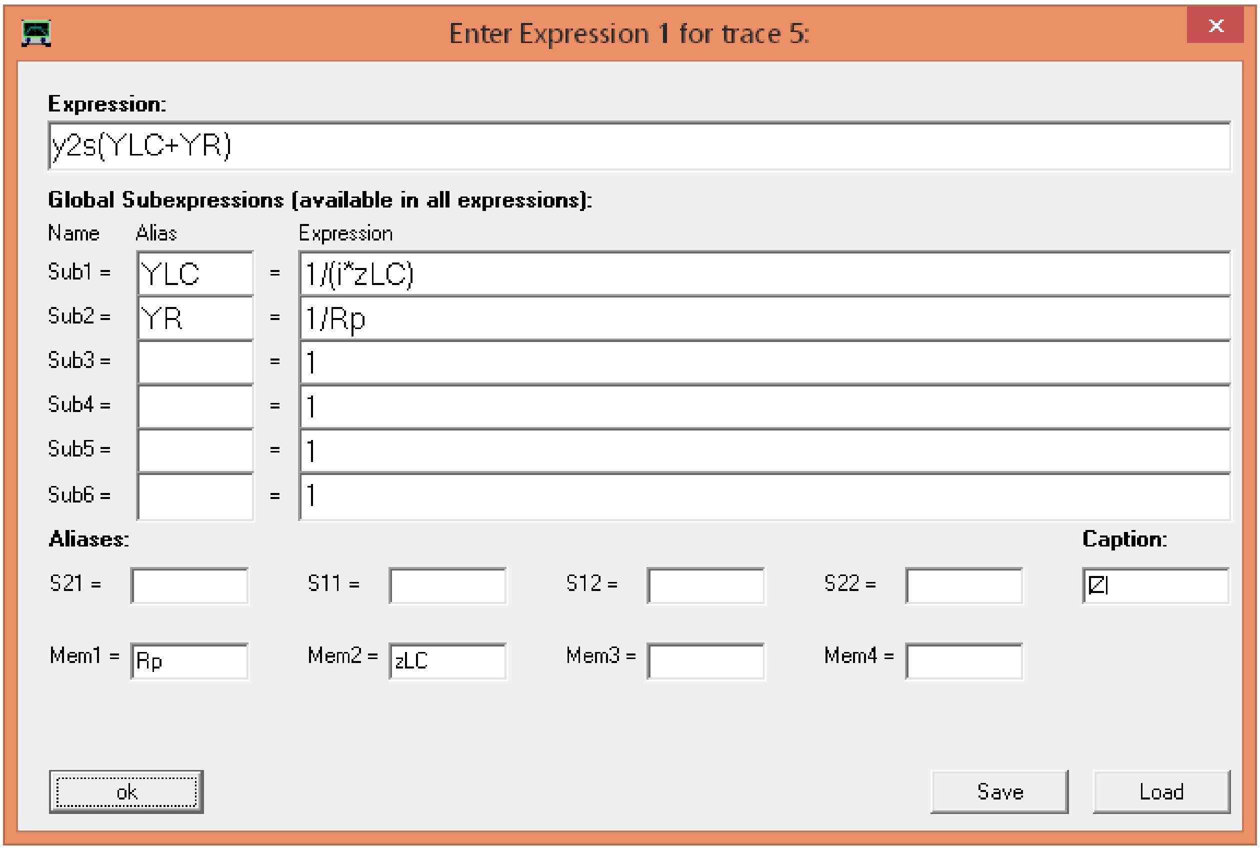
Next after the XL value imported as Magnitude from Column 4 to Mem2



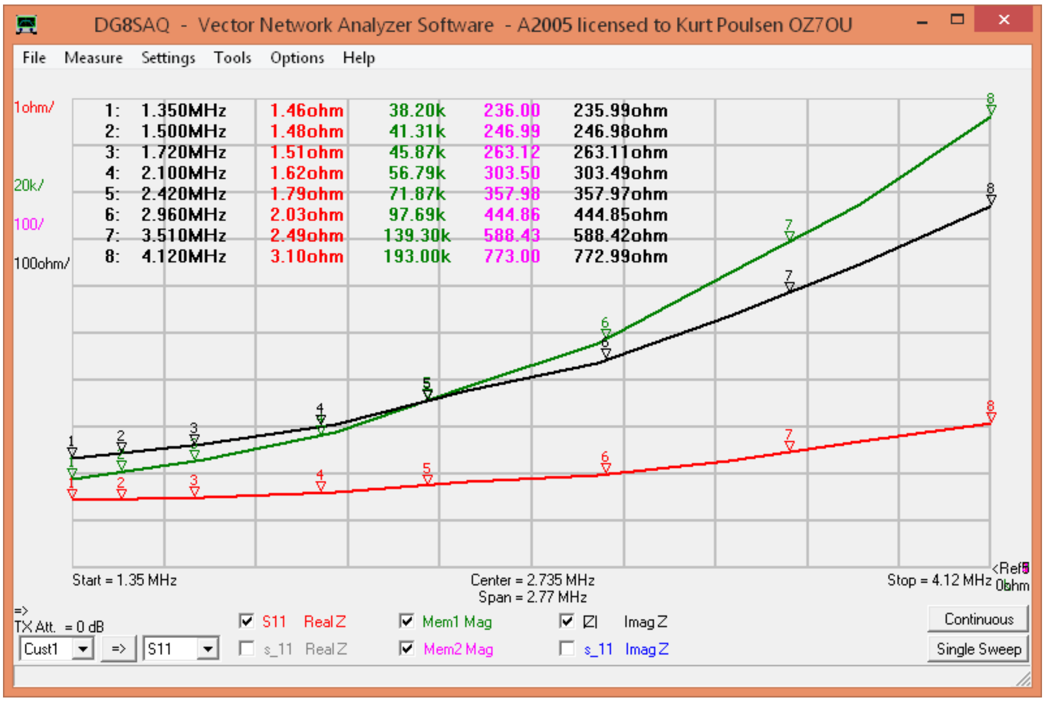
Now into the VNWA software we have Rp and XL as function of frequency available and can create the S parameters for the coil measured with the old Q meter.



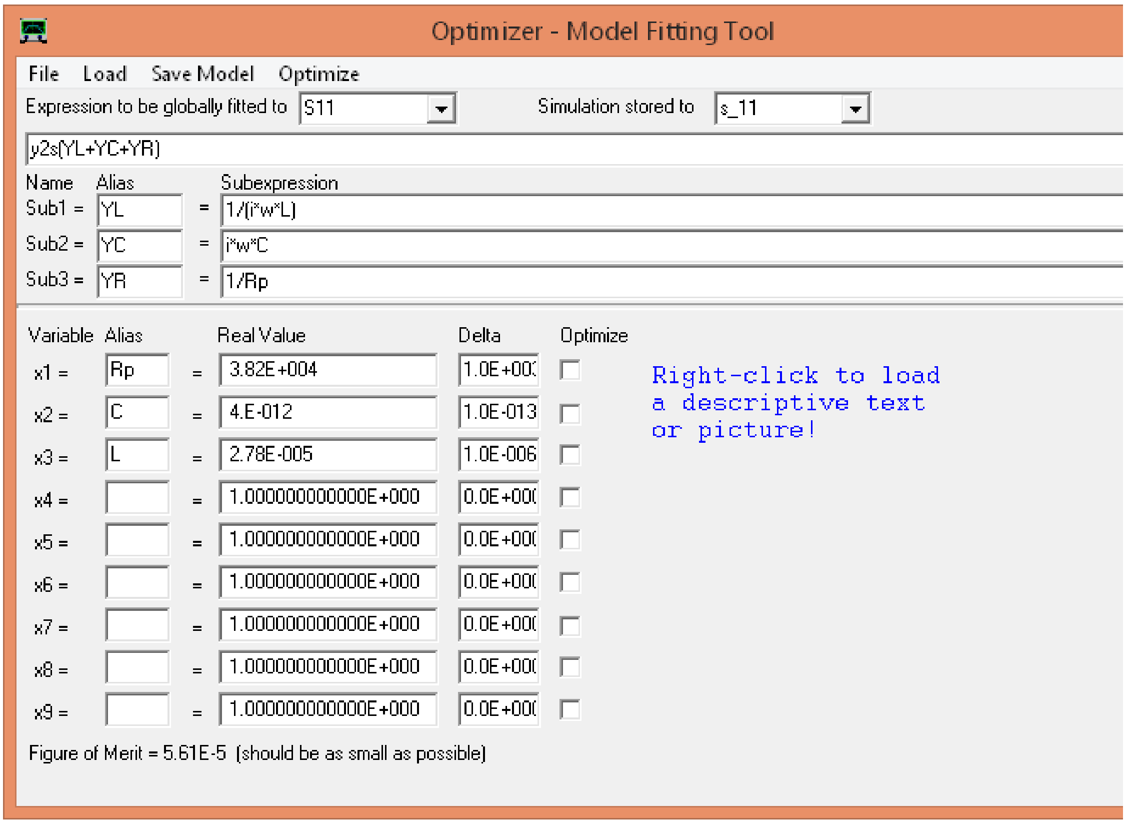
To do that we create a custom trace – trace 5. From Mem1 we have Rp and from Mem2 and we have the inductance with the included parrallel capacitance called zLC. As all three components are in parrallel we simply add their conductivity (i is the same as j) and we transform conductivity Y to S with the expression y2s. The custom trace called |Z| (the Caption:).



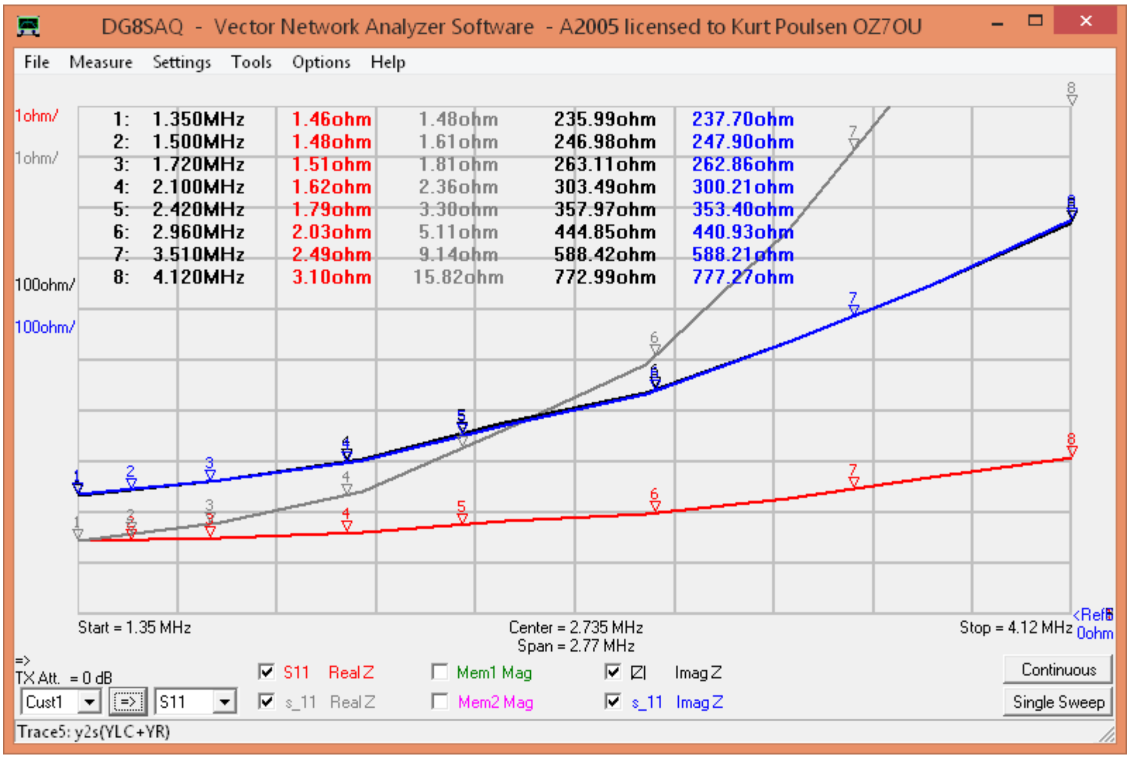
Trace 1 selected as S11 and RealZ and the Custom Trace 5 (Cust1) transferred to S11 by a click on the arrow lower left corner after selecting Cust1 as source and S11 as destination . Cust1=Trace 5 is set to ImagZ. This step important because the Optimizer Tool described next act on data stored in S11.



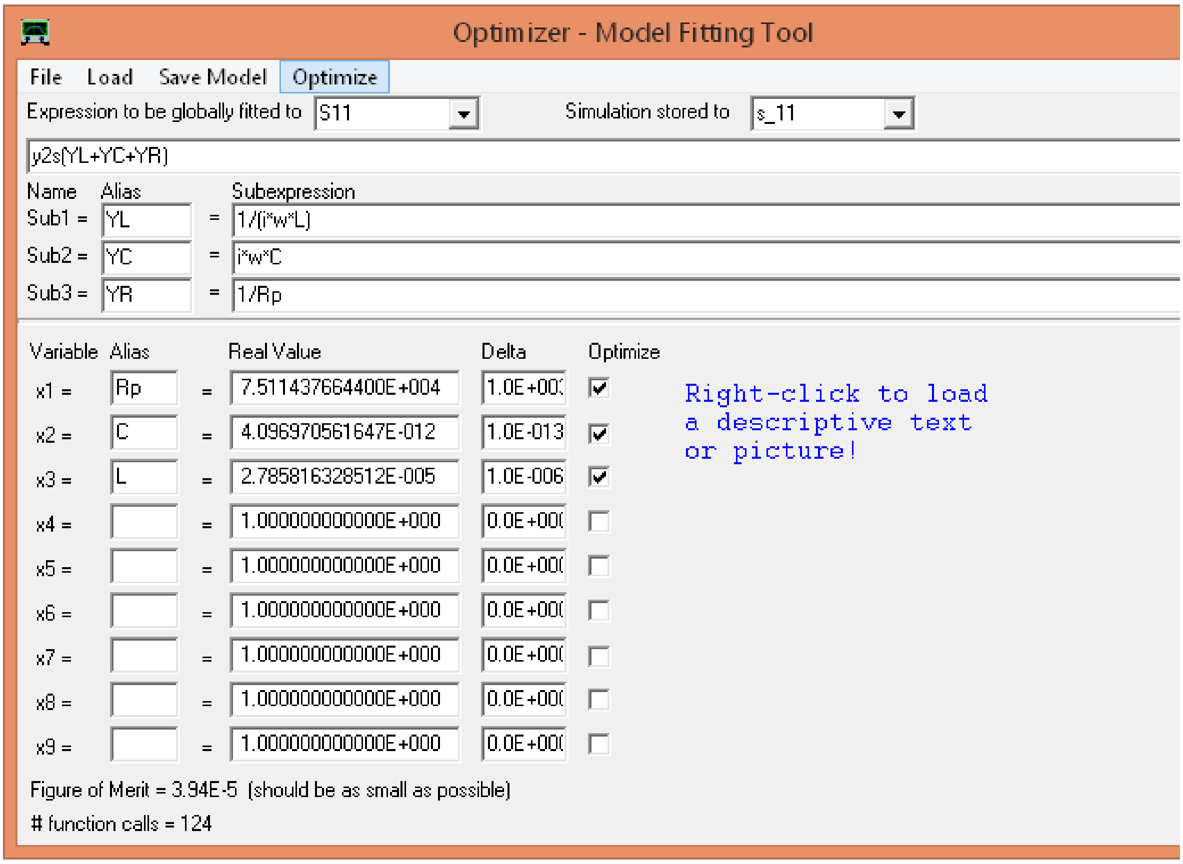
Next the new VNWA Tool Optimzer is opened and again we create formulas for our coil based on Inductance L Parralel Resistance Rp and the Shunt capacitance for the coil C. Like in the Custom Trace we use the conductivity Sub expressions being summed and by y2s transform from Y to S parameter. The great thing with the optimizer is that it dynamicly shows the entered data when entered/changed as the simulation is saved in s_11. So we enable two more trace s_11 ImagZ and s_11 RealZ. We enter data for the L, C and Rp based on best guess/present knowledge and select delta values about one magnitude less than data entered. Later we then by using the mouse scroll wheel can dynamicly change values for all three variables. If delta set to 0.00E+000 the value is fixed likewise if the tickmark in Optimize boxes is not set, the variable is not included in the Optimize process we are going to use.



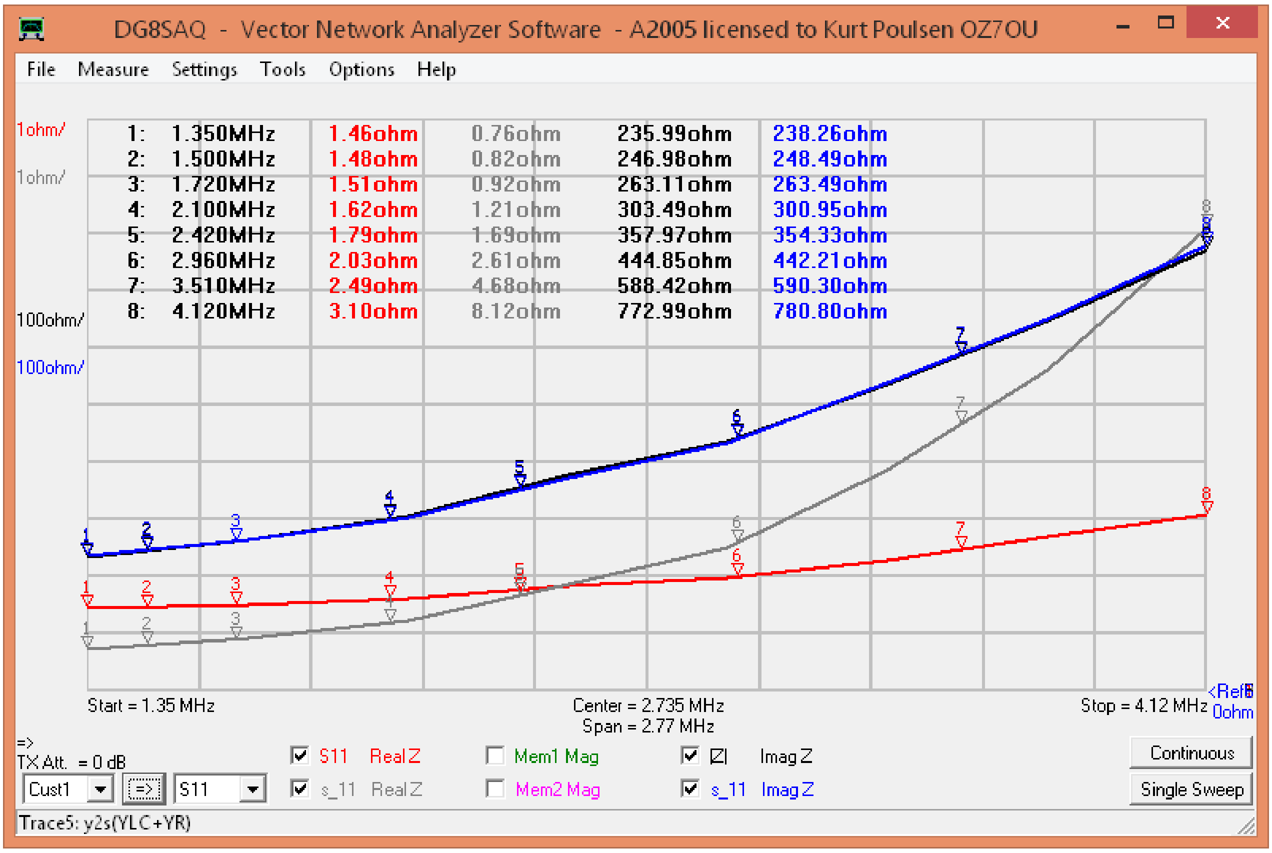
Below is seen the enterd value for the L (blue ImagZ) is pretty close to the L value from the Custom trace (Black ImagZ) wheras the two RealZ values differs. We will now run an Optimize process



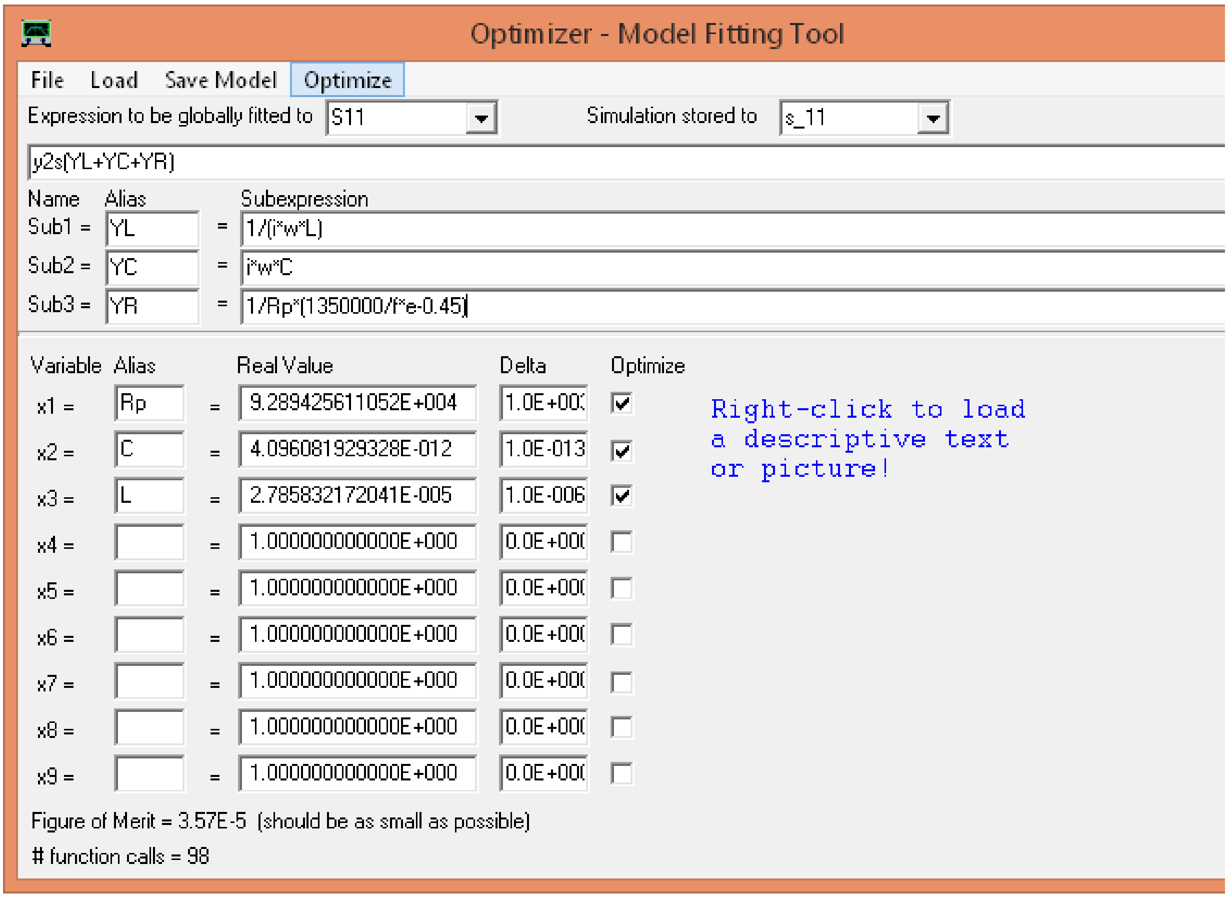
To run an optimize process we must enable the Optimize tick boxes and click on Optimize. The coil found to 27.86uH pretty close to the spreadsheet value at low frequency as expected, and the Shunt C to 4.1pF. The R value 75.1Kohm.



The simulated RealZ is deviating quite a lot and the is natural as we already from the Q meter measurement and the Spreadsheet graph has seen the Rs value is not constant across frequency range so we must add an expression for the frequency dependency and trim it until the RealZ fits the Q meter meaurements.

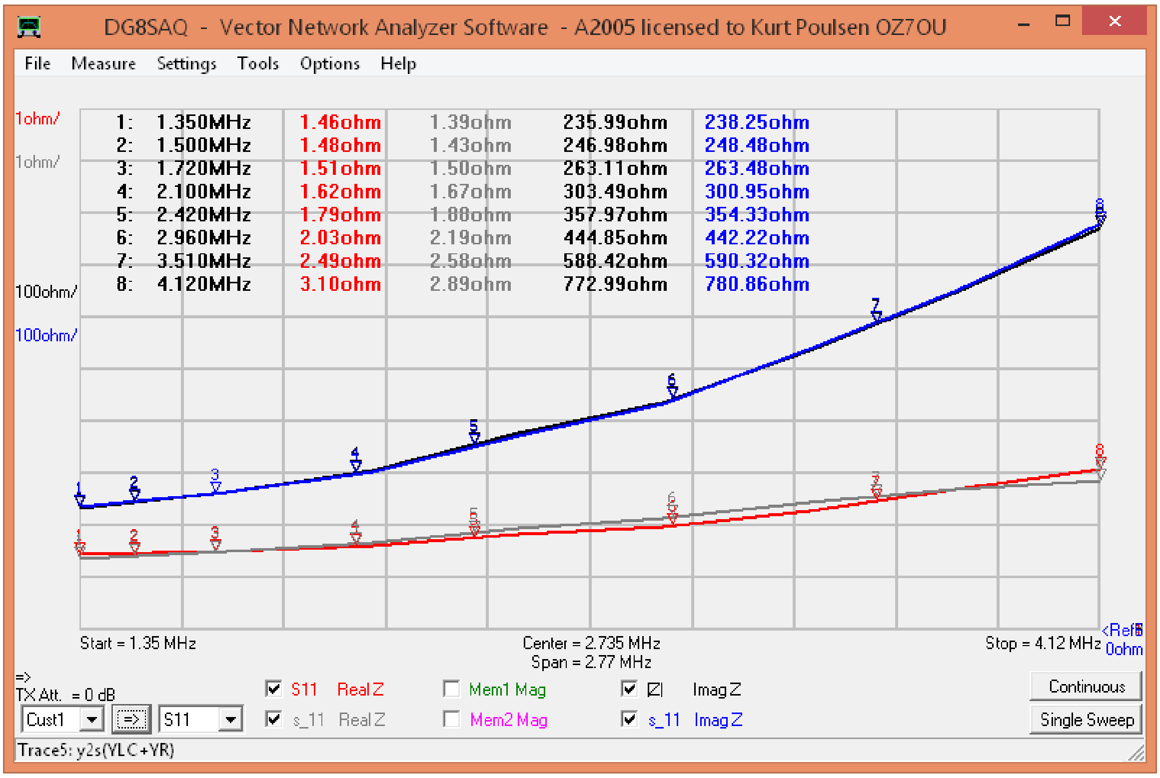


That is done by the addition of the expression for Rp *(1350000/f*e-0.45). !350000 is the lowest frequency and 0.45 quickly found by repeated run of Optimize.

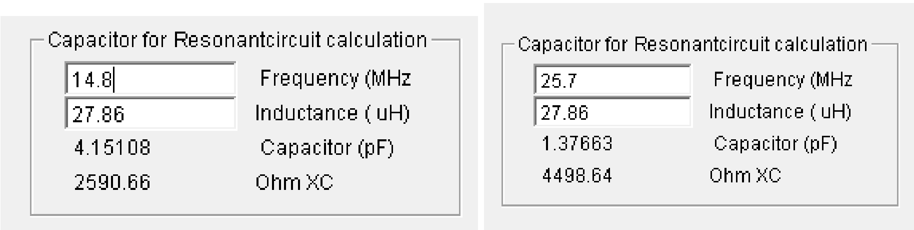


L still 27.86uH, C unchanged 4.1pF but R changed to 92.9Kohm

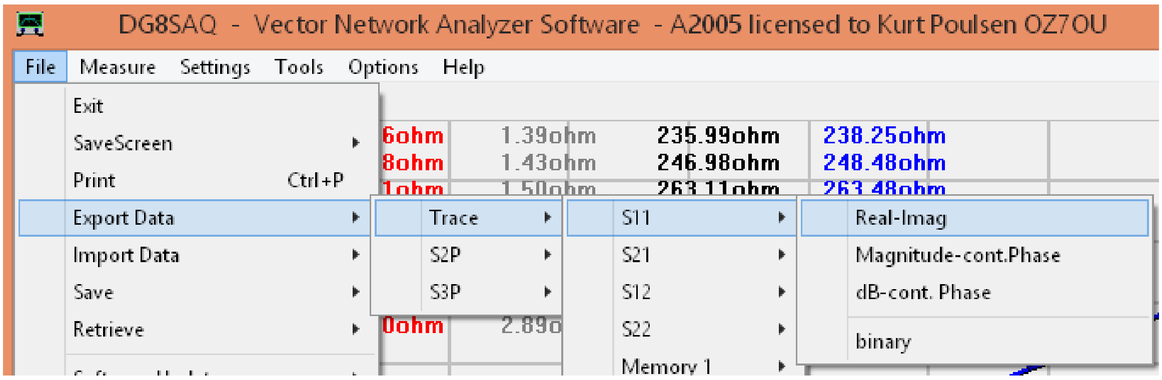
Excellent match and hardly possible to do better. Compare the table data for the 8 measurement frequencies.



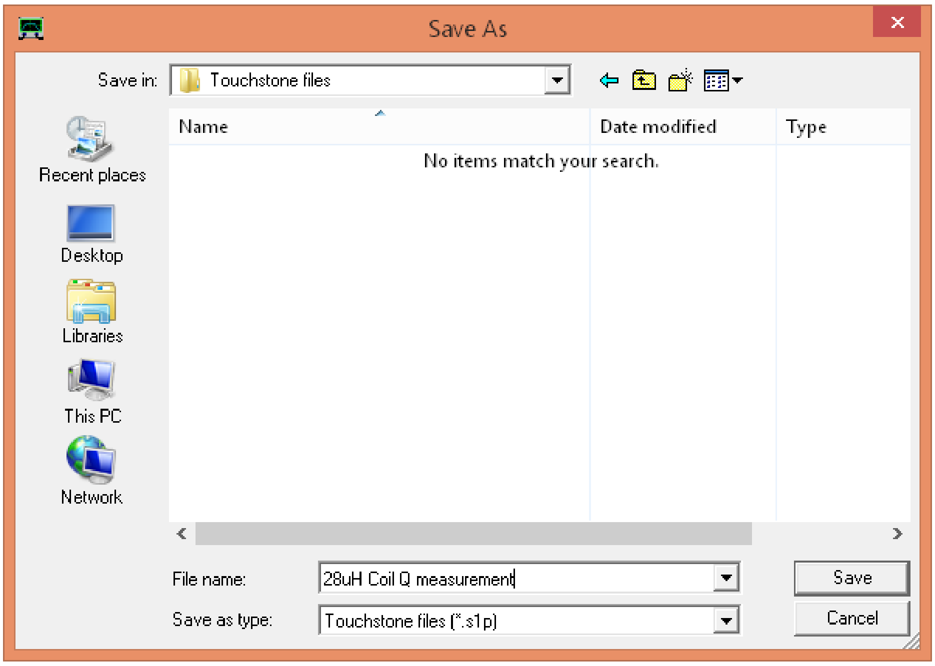
The found C value is identical to the measured resonance frequency 14.8MHz for 27.86uH and if the L is still 27.86uH at selfresonance as initial measured with the pick up coil then the shunt C is 1.37pF



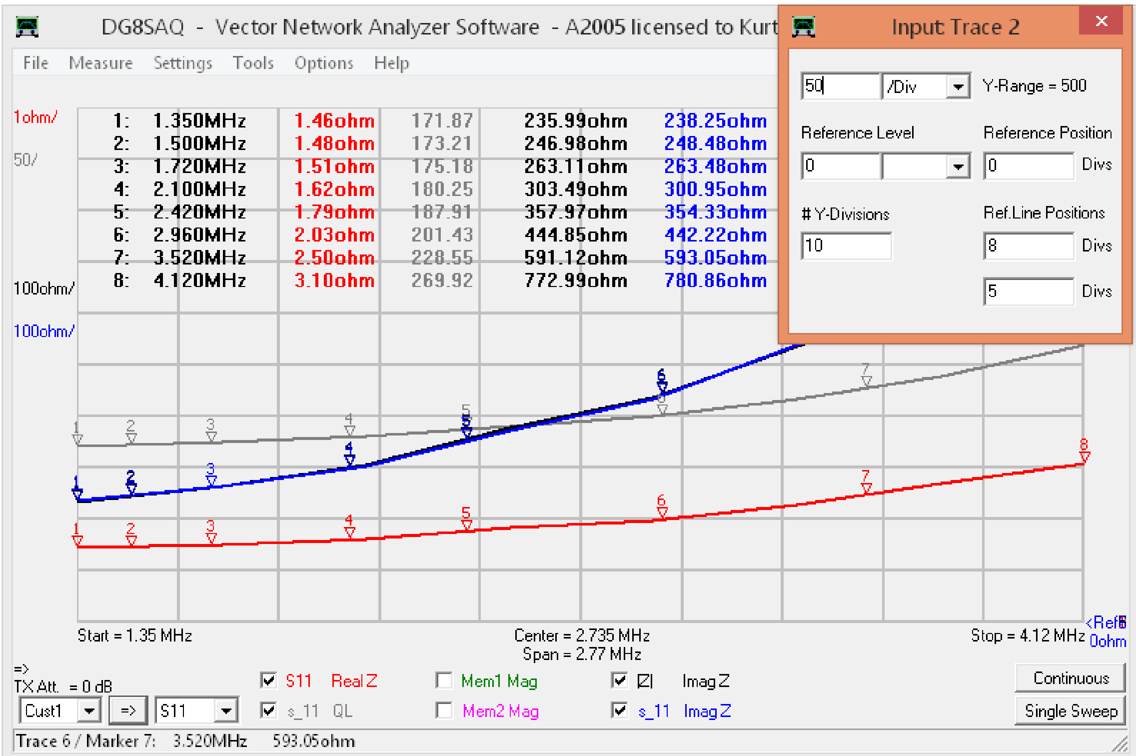
Now we can save the optimization to a touchstone files for later recalling if wanted



And grant a name to the Touchstone file



Finally we can change trace 2 s_11 from RealZ to Q and see the effect of the Shunt C compared to the spreadsheet data. At 1.35MHz the Q was 162 and simulation shows 171.9 at 4.14MHz the Q was 250 and simulation shows 269.9.



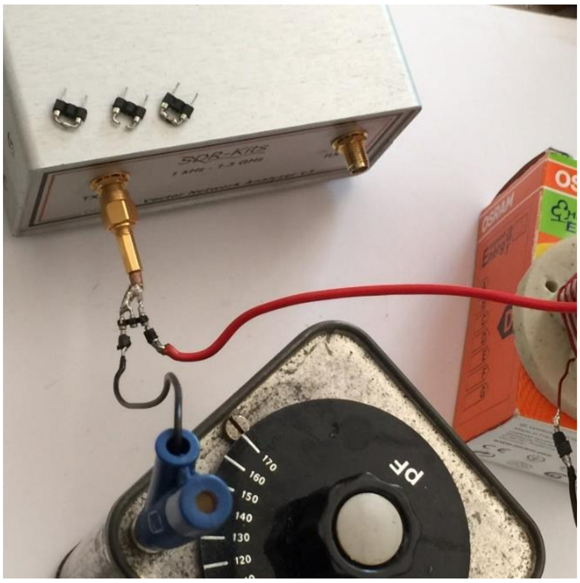
SO NOW TO THE INVENTION FINALLY

How can we simulate an oldfashion Q meter using the VNWA and avoid all the trouble with noisy Q traces ?

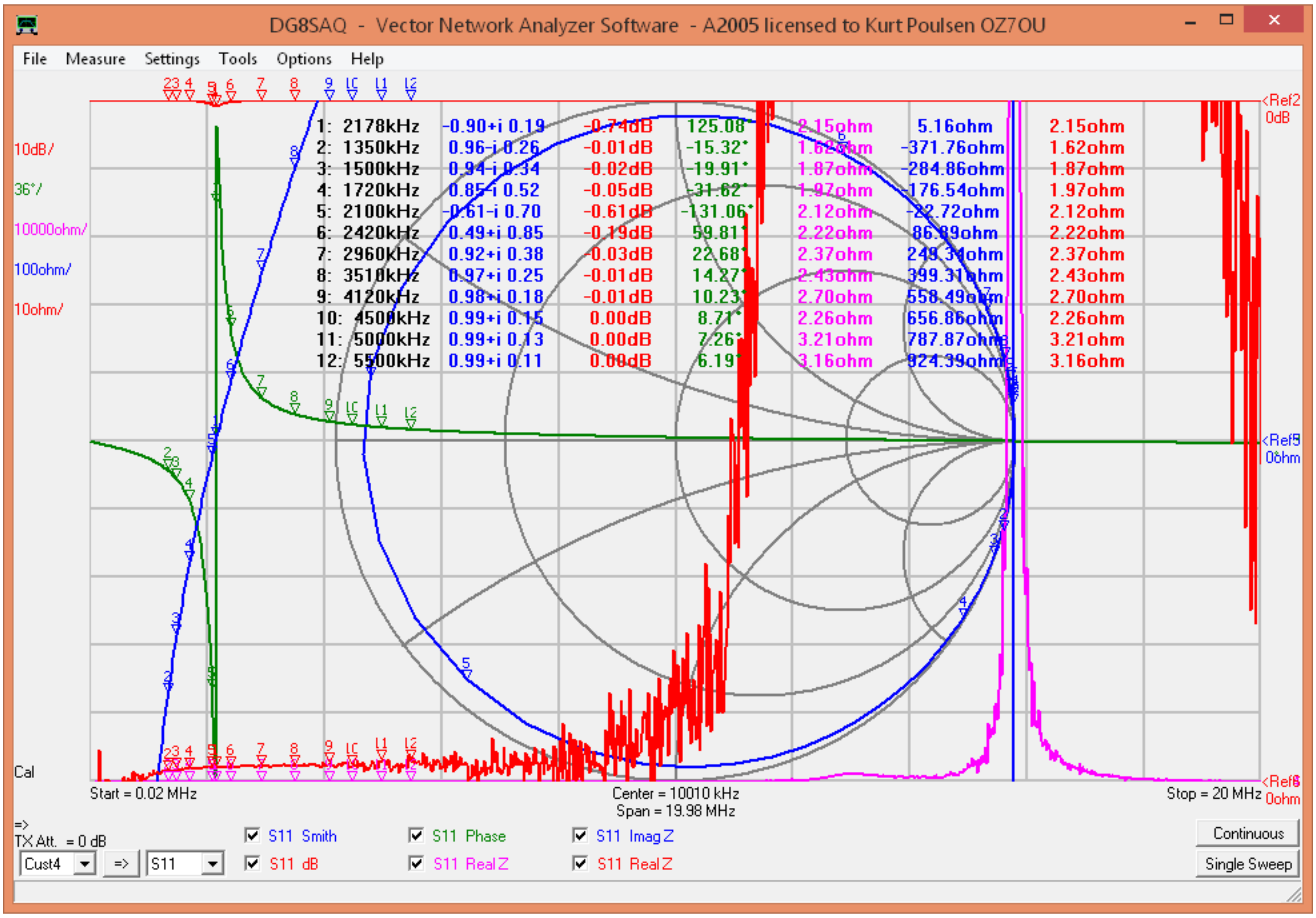
Simply by using this little device shown below and made by my dear elderly brother many years ago, long before the VNWA was invented:


We simply insert a lossless variable capacitor in series with our coil and we can precisely measure the low series resonance resistance by by a standard VNWA calibration ro even more precise using the V method with a T adaptor as External bridge and by anther VNWA tool find the Q value right away. That is going to be our virtually automatic Q meter .

THIS IS GOING TO BE FUN



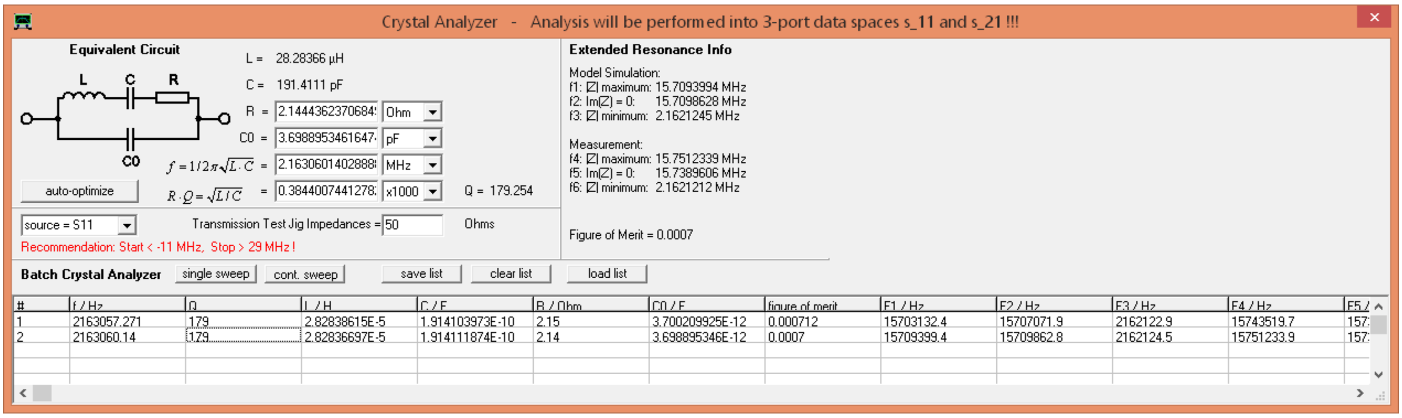

The variable capacitor is connected in serie with the coil and the VNWA calibrated with Short, Open, Load using the the small homemade calibration standards seen on top of the VNWA, where the load is made of two 100ohm 0.1% SMD 805 resistors. The frequency span so selected that we have the parrallel resonance well inside the sweept range here from 20Khz to 20MHz. Set the capacitor to full C which in my case is 170pF. A 500pF would be ideal but for demonstration of the technique this value is OK. You may use fixed capacitor but they must have very high Q values, preferable 100 times the coil Q at the measuring frequency. Look closely on below picture where the markers are set to the same frequencies as when the coil was meaured with the old Q meter so we can compare. Look closely of what I have selected of traces and Y scale settings . The phase when going from -180 to +180 degree is where the coil and the variable capacitor has series resonance. The wire from the VNWA to the variable capacitor and further on the coil and from the coil to the VNWA center conductor of the TX output is not changing the series resonance to any degree worth considering as the coil is 28uH and a 10cm 1,5mm wire has inductance of 0.1uH. See http://chemandy.com/calculators/round-wire-inductance-calculator.htm



Already wee see after a sweep the series resistances (RealZ) are measured without much noise in the trace. The marker 1 placed at the transition for the phase and that is the same place where ImagZ passes throught 0 ohm at division 5. Comparing with the spreadsheet we are within about 10%.

But we are not finished with surprises yet.

Now we open up for the Tool Crystal Analyzer. When a sweep is run we see the following. 2 single sweep processed.

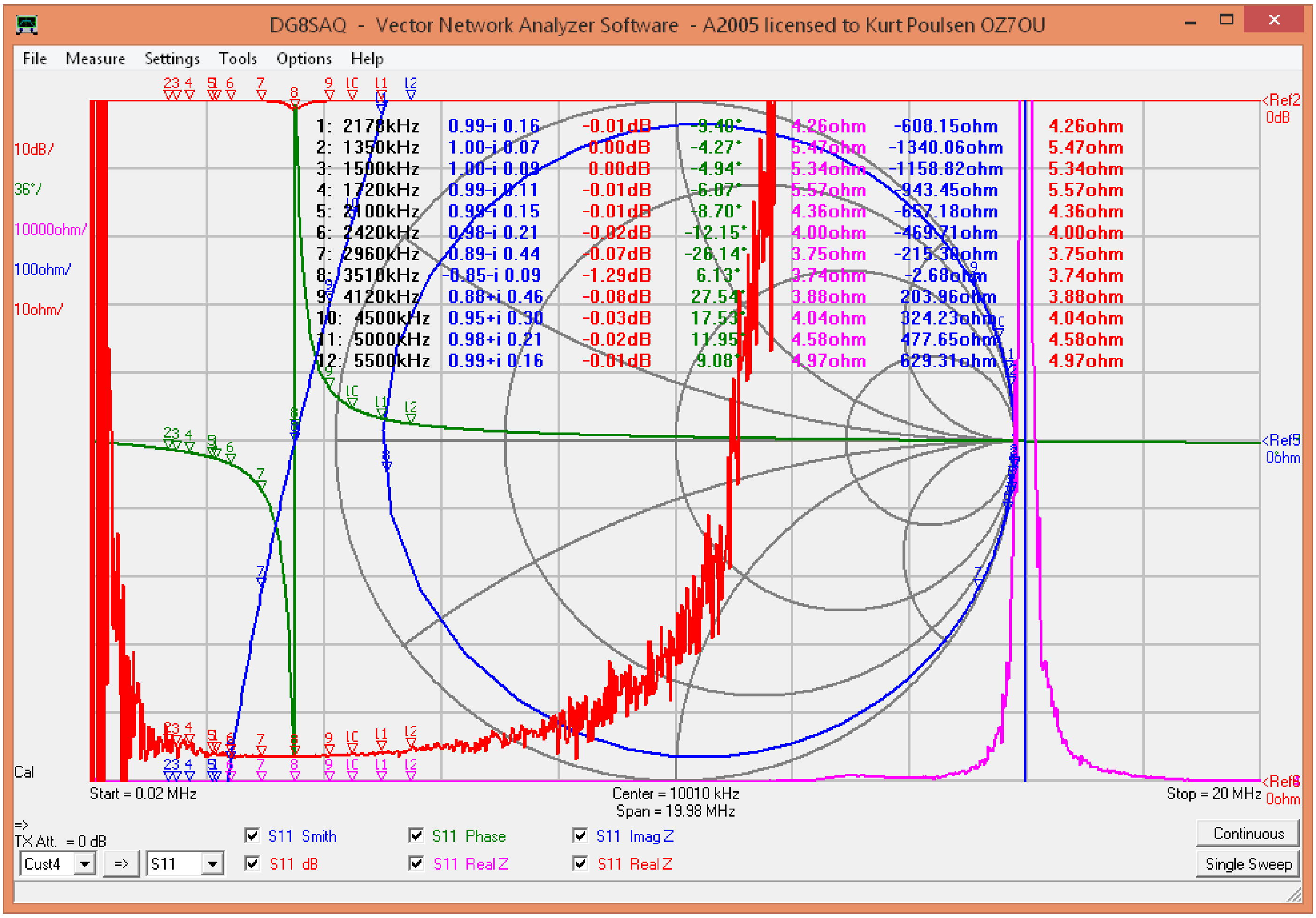


With this tool we find the inductance L 28.28uH, the series resistance R 2.15ohm, the tuning capacitance C 191pF and the shunt capacitance C0 3.7pF. We even find the series (2.163MHz) and parallel frequencies (15.7MHz) and our wanted Q value 179. A second run shows exactly the same value. That is amazing !!!!

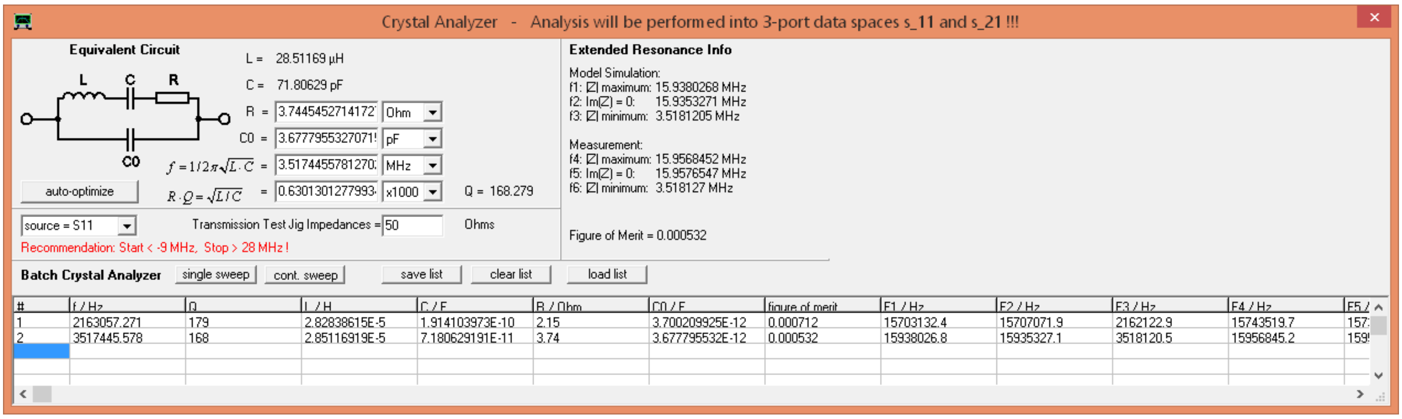
Regarding the C value of 191pF I control meaured the variable capacitor with the VNWA incl. the connection wires and at 170pF setting the measured C valie was …surprice surprice 190,5pF.

<u>But we do not need to know the capacitance.</u>

Now just let the sweep run in continous mode with a small value for time per point e.g. 2ms, and tune the variable capacitor until you find the phase transistion at the frequency where you want to find the Q value of the coil and then change back to long time per point e.g. 30ms, then run a single sweep and see it is OK and then go back to the Crystal Analyzer and let it do the hard work. We will just repeat that for the frequency 3.510MHz



Everything look good

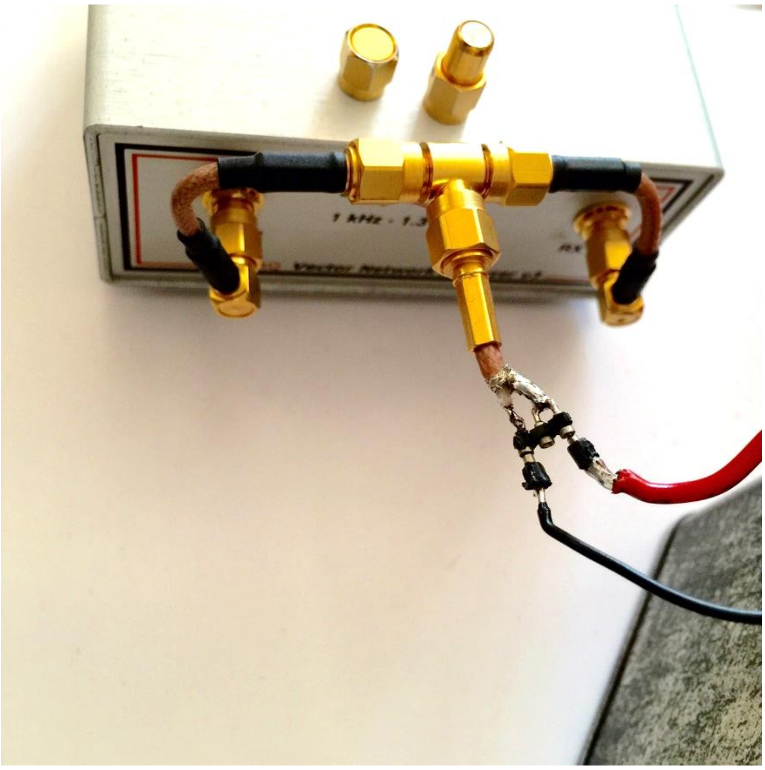


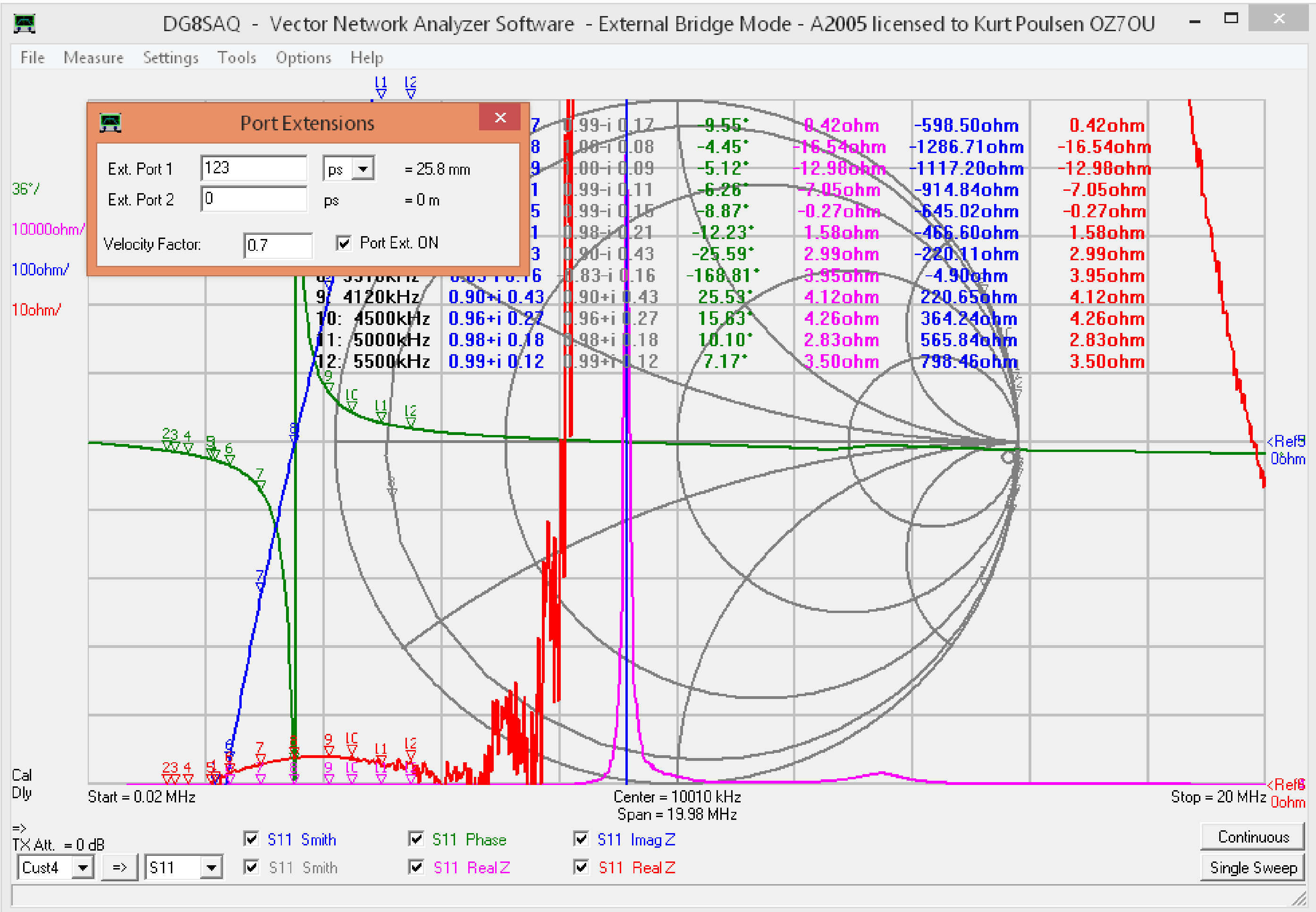
I marked line 2 before the single sweep and the new measurements are inserted at line 2. I get warning about the "fitting failed" but still it does a nice job. You mat tweeke span setting to get rid of the warning. When done the measurements for the frequencies of interst, you can save the data as a spreadsheet by a click on "save list".

To improve the measuring accuracy for low impedance values (for the RealZ values) the V method, using a T adaptor as external bridge might be better and we just repeat the last setup using that method.

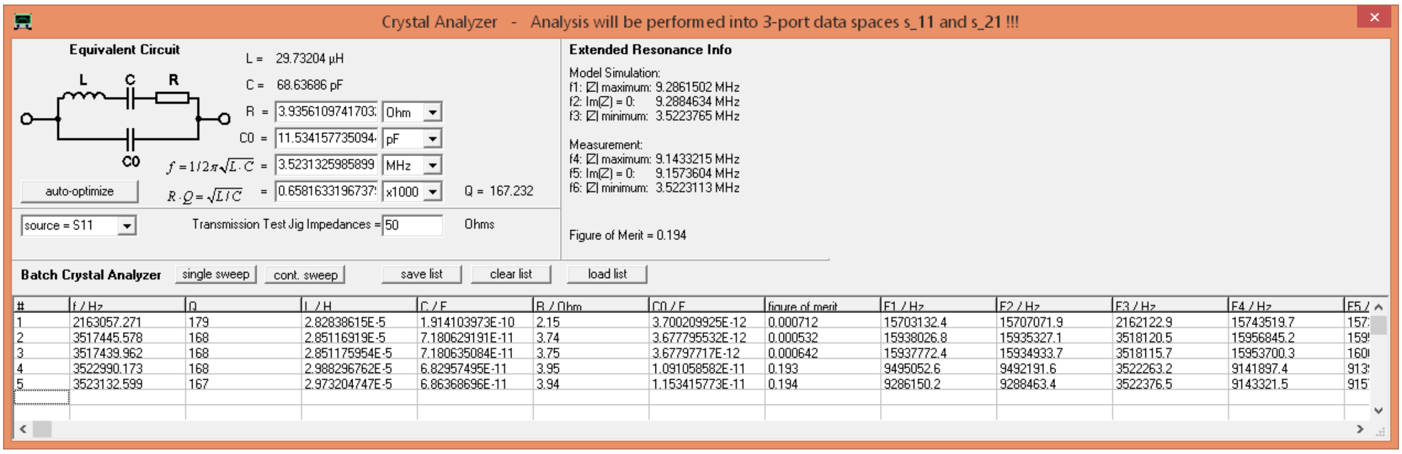
Note: Before doing so just a note on Smoothing which can clean up the traces for noise. Then by a right click in the cleaned trace you can save to a file and import it again to VNWA for further processing with the ASCII import Tool. But that goes too far for this report, just a note for pointing out the possibility.

For this V method and to ensure optimum calibration I used a calibration kit with Rosenberger Male Load and Fairview male short from SDR-Kits. To compensate for the male SMA adaptor with the short cable and the bushings for connection the coil/variable capacitor assembly, is used the extension Port1 delay function. Delay found to be 123ps by measuring phase and tune the delay to 0 degree when no wires connected to the bushings.





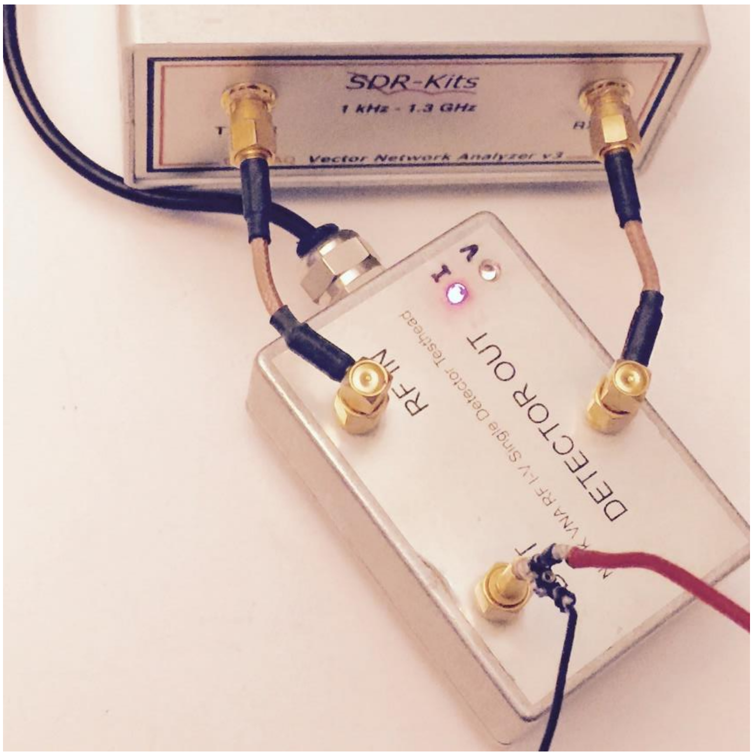
However the parallel resonance is lowered considerable to 10MHz from 15.7MHz. The V method is very poor to meaure high impedances so we must see how that impact the Crystal Analyzer calculations. The V method measurements are line 4 and 5. The F, Q and C calculations are identical and C slightly lower but C0 11pF due to the detuned parrallel resonance.



Grande Conclusion regarding the virtual Q meter.
The standards VNWA calibration is best choice for our virtual Q meter. The Q values measured with the good old Q meter are about 10% to 20% higher. The measurement with the VNWA has additional series resistances involved by the contact resistances in the small bushing/pin and bananaplugs etc. which will lower the Q. All wires should be soldered and calibration by using a “real” calibration kit (Rosenberger). The added SMA adaptor must be with a very short cable (less than 10mm) for soldering the wires to the coil/variable capacitor and compensate for its exsistence by Extension Port 1 delay as described a couple off times earlier.
Putting the coil inside the bid paint can might be an idea for improvement.

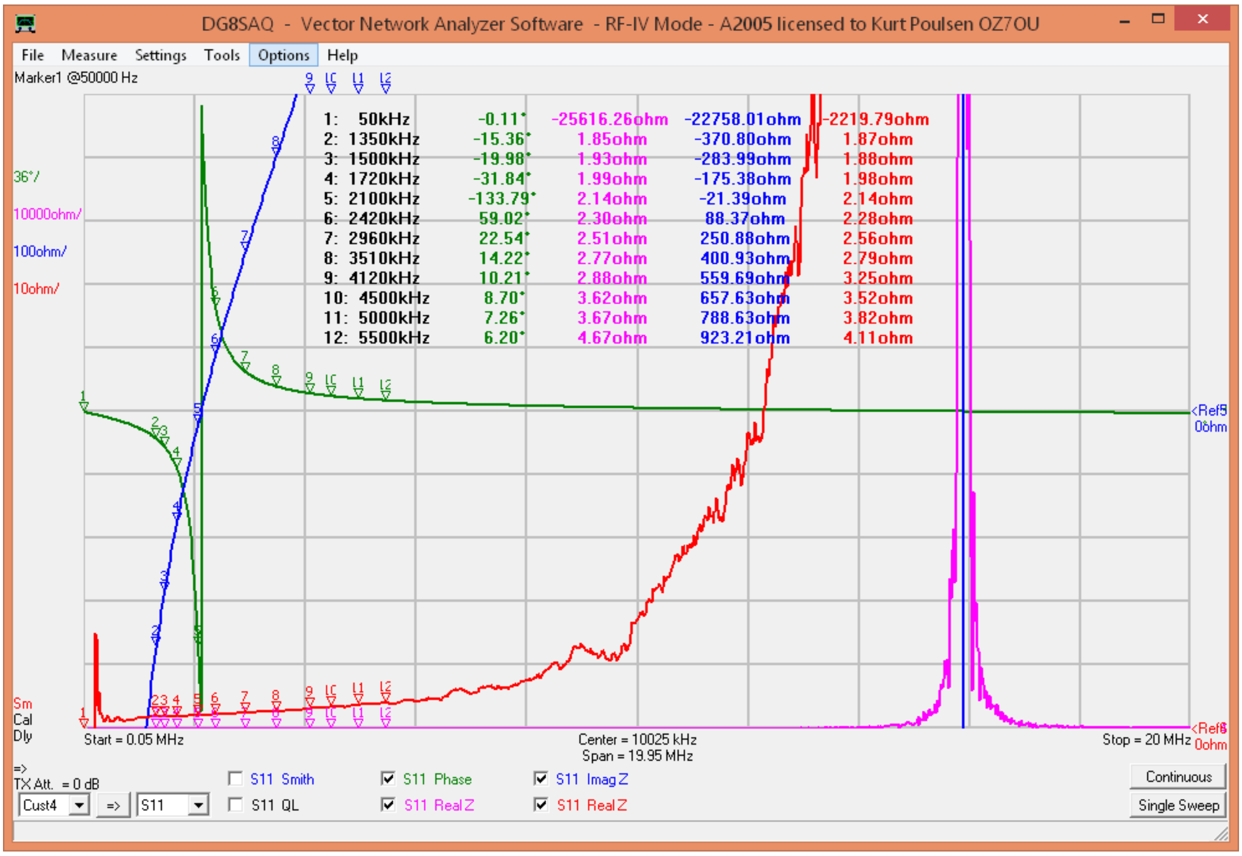
Appendix about the N2PK RF-IV adaptor

The N2PK R-IV adaptor supported is a very stable adaptor for reflection measurements and equally accurate for low, medium and high impedances. For below meeasuremetns I also removed the power plug to the LapTop so it was running on battery to minimize the coupling between coil and wiring.

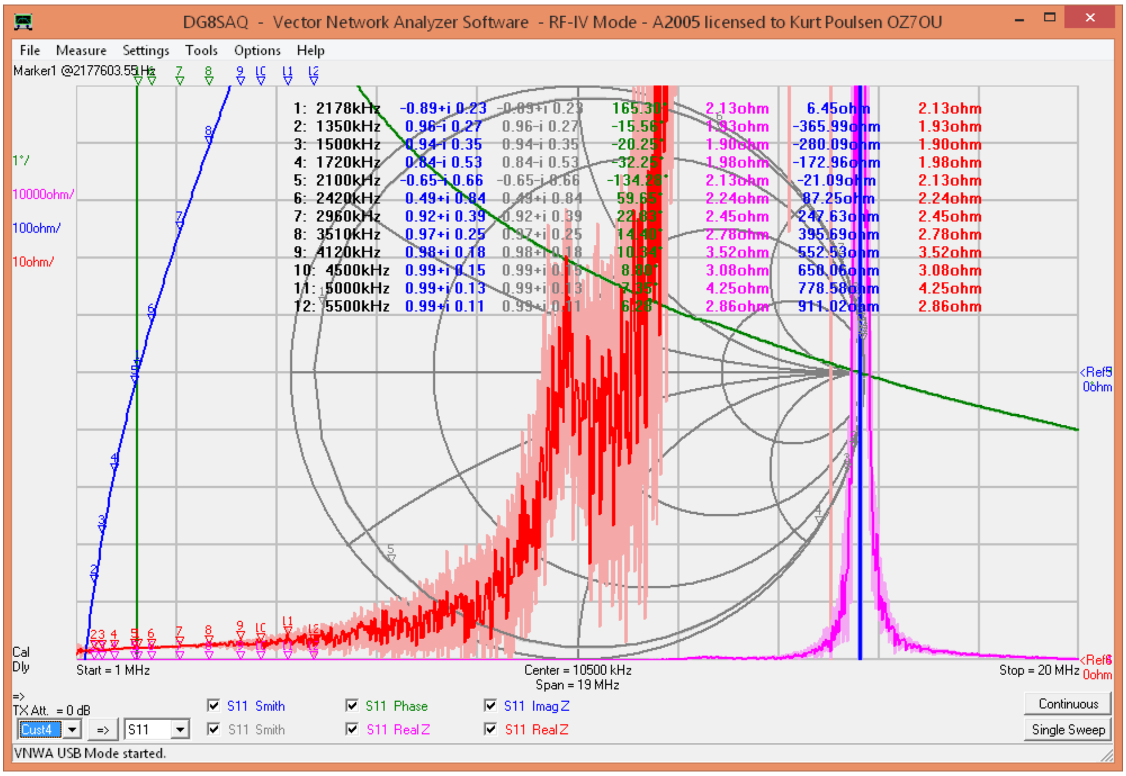


Below screendump of the coil with 1% smoothing (10 point out of 1000 points) for trace 2 and 6 shows Q values extremely close to those measured with the Old Q meter. I have also removed the power plug on the LapTop so it runs on batteries which has a positive effect on the meaurement stability as discussed earlier.

The variable capacitor at 170pF and coil in series demonstrates acceptable correlation with the old Q meter measurements taking into account the variable capacitor and the bushings/pins used will add som loss



In particular the long term stability is superb. The image below demonstrates measurements with screen storage switched on and with continuous sweep for 7 hours Even after three hours of laptop shut down it was bang on when cold started.



Have fun with you measurement of coil parameters

Kind regards

Kurt de OZ7OU

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