# Tuned LC circuits.

## Frequency

A tuned circuit made of a coil L (unit: Henry) and a capacitor C (unit: Farad) has the following resonance frequency:

**f.res = 1/(2.pi.root (L.C))**

Example: a coil of 0.2 mH (0.0002 Henry) is connected to a 500 pF tuner capacitor (0.000,000,000,500 Farad).
The lowest frequency we can tune to is 503 kHz.

If we turn the value of the tuner capacitor to a value of 48.8 pF, the resonance frequency will be 1611 kHz.
Here in Europe 1611 kHz is the highest frequency on medium wave.
So, with this LC circuit we can tune over the entire MW band.
In practice both coil and detectordiode will have a certain capacitance, so we must set the tuner capacitor to a lower value for tuning at 1611 kHz.
If the coil has too much capacity it is possible that we can't reach the highest frequency.
In this case we can add some space between the turns of the coil, this will reduce capacity.

## Bandwidth

At resonance frequency the impedance of a parallel LC circuit will reach it's highest value, the voltage over the circuit will then also reach it's highest value.
Above and below the resonance frequency the voltage will decrease.
There are two frequency's where the voltage is 0.707 times the voltage at f.res.
One frequency is just below f.res, this is frequency fl.
And one frequency ia above f.res, this is frequency fh.

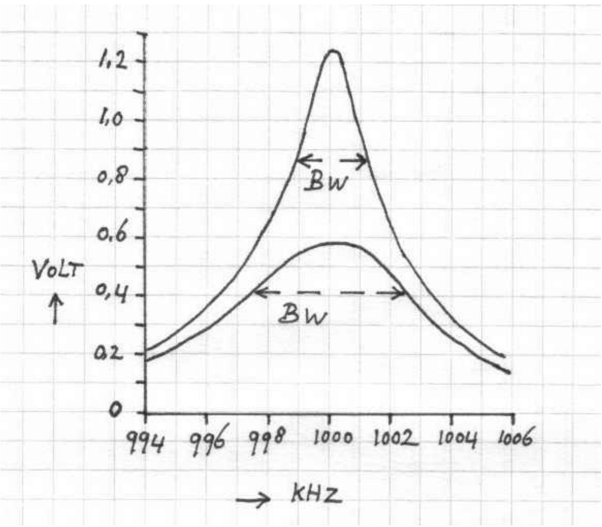
The voltage reduction to a factor 0.707 is a reduction of 3 dB
The current is there also reduced to 0.707, and so the power in the circuit is halve the power of f.res. (0.707 x 0.707 = 0.5).

The bandwidth of the tuned circuit is: **BW =fh - fl**

## Circuit Q

The Q of the circuit is:: **Q=f.res / BW**

The higher the Q, the smaller the bandwidth, which is better for separating adjacent stations.
And also, the higher the Q, the higher the voltage which the received station gives over the circuit, so a more sensitive receiver.



Curve of frequency respons for two tuned circuits.

At the upper curve, the bandwidth is 2.4 kHz.
The Q is 1000 / 2.4 = 416

In the lower curve the bandwidth is 5 kHz.
And here the Q is 1000 / 5 = 200.

The Q of a circuit can vary from less then 100 for coils made with massive wire, up to 400 or more for coils made with litzwire.

The Q of a LC circuit will decrease when we connect a antenna or detector to it, this is because the antenna or detector gives extra parallel resistance to the circuit.
By doing this the selectivity of the circuit will reduce.

## Parallelresonance

In a parallel LC circuit, the impedance will be high in resonance.
If the coil and capacitor has no losses, the impedance would even be infinite at resonance.
In practice this is not possible,there will always be losses, for instance in the resistance of the coilwire.
So, the impedance is not infinite, but has a certain value, it looks like there is a resistor connected parallel to the LC circuit, this we call the parallelresistance of the circuit "Rp".

**Rp=2.pi.f.L.Q**

## Parallelcircuit with taps on the coil

As discribed above the parallel LC circuit has a certain parallelresistance.
For maximum sensitivity in a receiver, the load impedance (speaker or audiotransformer) must have about the same value.
If we only have a speaker or transformer with a lower impedance, then we can connect the detector diode at a tap on the coil, instead of the top of the coil.
The circuit will then not be loaded too much, and the Q and selectivity will not drop.

The table below gives the value of impedance and voltage on the tap's of the coil.
Also the current is given which can be given at the tap, the current will increase at a lower tap.

| Tap | Voltage on tap | current | impedantie |
|---|---|---|---|
| 100 % | 100% | 100% | 100%.Rp |
| 90% | 90% | 111% | 81%.Rp |
| 80% | 80% | 125% | 64%.Rp |
| 70% | 70% | 142% | 49%.Rp |
| 60% | 60% | 166% | 36%.Rp |

| | | | |
|---|---|---|---|
| 50% | 50% | 200% | 25%.Rp |

The used diode must also have about the same resistance as the impedance at the tap.
Because of the lower voltage at the tap's the diode efficiency will decrease however, and this will reduce the sensitivity of the receiver.
The best option is the diode at the top of the coil, and the use of a load impedance with a high enough value.

## Series resonance

In a series connected LC circuit, the impedance will be low at resonance.
If there are no losses in coil and capacitor, the impedance will be zero Ohm at resonance.
But here are also always losses, in serie resonance we keep a certain resistance Rs.
The higher the Q, the lower the series resistance Rs.

**Rs=(2.pi.f.L) / Q**

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The Q factor of a unloaded LC circuit is determined by the following factors: series resistance in the circuit, parallel resistance across the circuit and magnetic losses.

**The series resistance in the LC circuit**,
the lower the series resistance the higher the Q.

The total series resistance in the circuit (Rs) is the sum of:

**The wire resistance of the coil**, thicker wire or litzwire with much strands helps to reduce wire resistance.

**The resistance of the capacitor plates**, silvered plates gives the lowest resistance.
Plates with oxide gives more resistance than clean plates.

**Contact resistance between rotor and frame of the variable capacitor**, preferable the variable capacitor has a spring connected to rotor and frame, this provides a low resistance.
When the contact is made with a slidercontact at the rotor, this must be clean and free of oxide.

**The parallel resistance across the LC circuit,**
the higher the parallel resistance, the higher the Q.

Parallel resistance across the circuit (Rp) is caused by dielectric losses.

There are:
Dielectric losses in the coilformer
Dielectric losses in the insulation of the coilwire
Dielectric losses in the insulators of the tuning capacitor
Dielectric losses in materials placed near the coil or tuning capacitor, look here for more information about this subject.
If the capacitor plates are not clean: dielectric losses in the dirt and oxide on the capacitor plates.

Also there can be a leaking resistance in insulators, e.g. by moisture.

All these losses together makes a parallel resistance (Rp) across the LC circuit.

### Magnetic losses

This occurs when a magnetic material (iron) is placed near the coil.
Non magnetic materials (plastic, wood, aluminium etc.) don't give magnetic losses.

### Why is the Q factor not constant for all frequencies?

The series resistance Rs gives a reduction of Q.
If we leave other losses out of consideration, the Q will have a value of:

**Q= 2.pi.f.L / Rs**

If the value of Rs is constant, the value of Q will increase with increasing frequency (f).
A series resistance in the circuit will especially give a reduction of Q at lower frequencies.

On the other hand:
if we only look at the losses caused by the parallel resistance Rp, the Q will have a value of:

**Q=Rp / (2.pi.f.L)**

Here we see, that at a constant value of Rp, the Q will decrease with increasing frequency (f).
A parallel resistance across the circuit will especially give a reduction of Q at higher frequencies.

The value of Q will both depend on series and parallel resistance, it is possible that a LC circuit gives a increasing Q at increasing frequency (because of series resistance) and than Q will reduce (because of the parallel resistance).
In this case we have a peak in Q somewhere in the frequency band.

Often the losses caused by the parallel resistance are the highest, and we only see a reduction of Q at higher frequencies in the medium wave band.
Than there is also a peak in Q, but this occurs at a frequency lower than we use.

## Coupled circuits

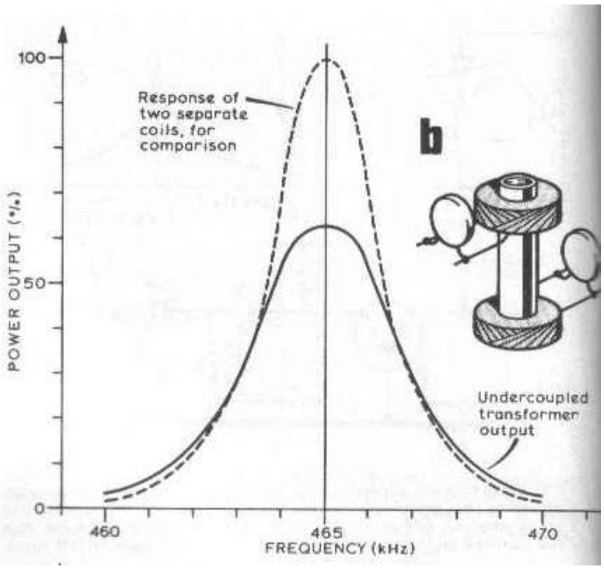
In a receiver having two tuned circuits, both circuits must be tuned to the same frequency.
De 2 coils of the tuned circuits must have a certain distance in between, via the magnetic field around the coils, the circuits are coupled to each other.
The distance between the coils determines the degree of coupling, the smaller the distance, the higher the coupling.

The -3dB bandwidth of a coupled circuit is higher than with a single tuned circuit.

The suppression of frequencies at some distance from the tuning frequentie is in a coupled circuit better than with a single circuit, this is good for suppressing strong local station.

In the pictures below you see the response of the coupled circuit at different degrees of coupling.
For comparison the response of a single tuned circuit is shown as a dotted line.

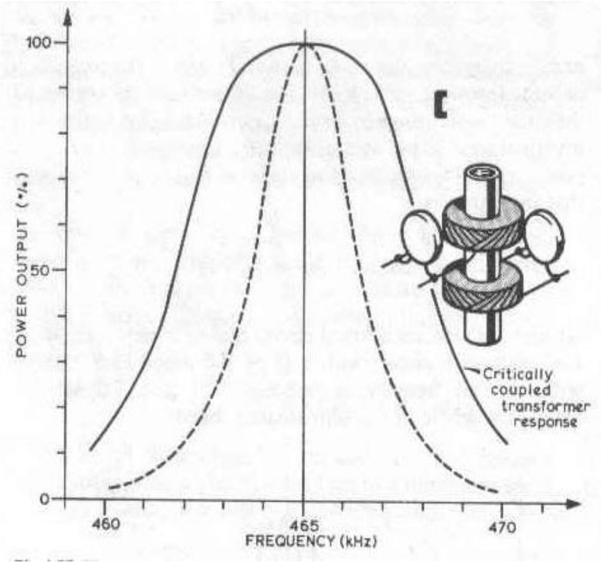
The pictures are taken from a radiohandbook, and are about a coupled filter for 465 kHz, but the theory is usefull for all coupled circuits, so also for crystal receivers with two tuned circuits.



**Undercoupling**
The coupling between the circuits is too low, because the distance between the coils is too high.

There is no maximum powertransfer from one coil to the other.

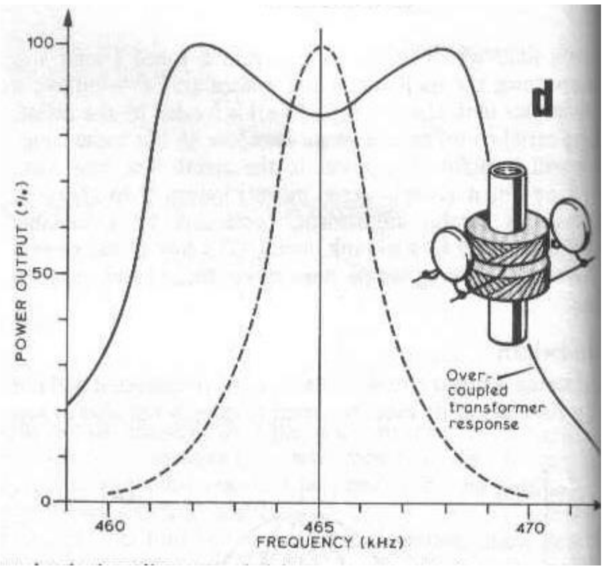
The bandwidth is higher compared to a single circuit.



**Critical coupling**
There is maximal powertransfer.

The bandwidth is higher than in a single circuit, and also also higher than a undercoupled circuit.

The response curve is flat in the top over a smal part.



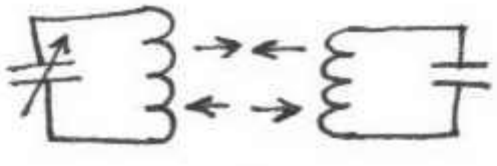
**Overcoupling**
The coupling is too high because the distance between the coils is too small.

The bandwidth is too high.

The curve shows two peaks, the higher the coupling , the higher the distance between the peaks, and the deeper the dip between the peaks.

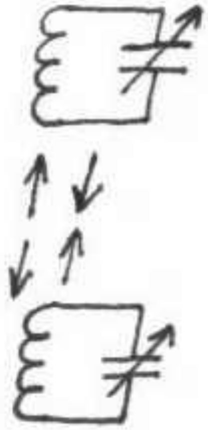
The critically coupled circuit is the best compromis between sensitivity and bandwidth.

Ther are several methods for adjusting coupling.
The methods shown below are mostly used in crystal receivers.



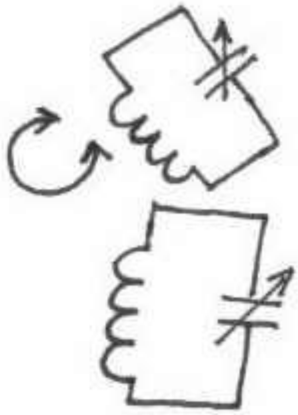
The coils are side by side

Coupling is adjusted by varying the distance between the coils.



Coils behind each other.

Coupling is adjusted by varying the distance between the coils.

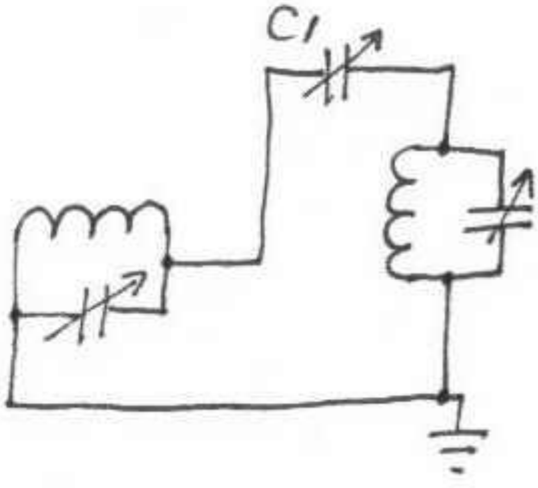


One coil is turnable.

Coupling can be adjusted by varying the angle between the coils.

With both coils in the same direction, the coupling is maximal. Turning the angle towards 90 degrees, the coupling will decrease.

With a angle of 90 degree, there is no coupling at all.



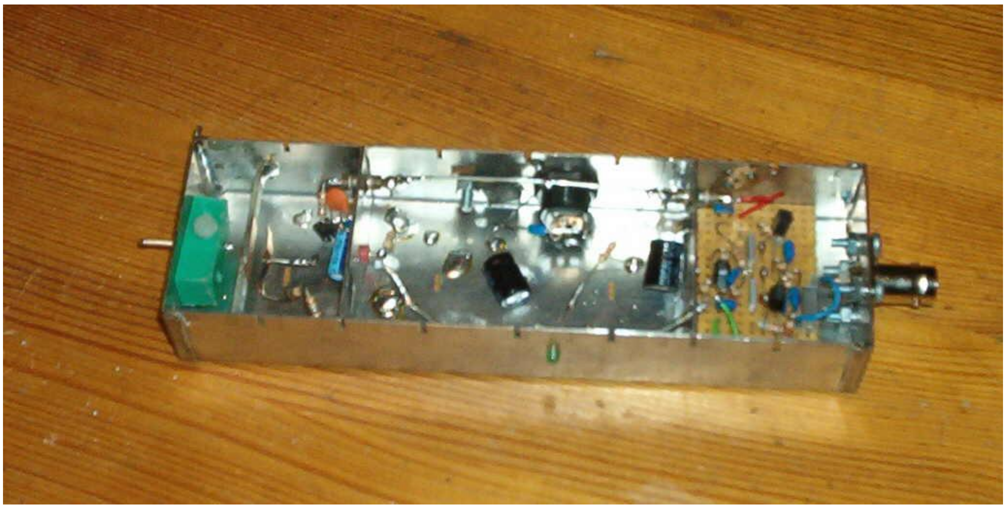
Capacitive coupling

Coupling is adjusted by a variable capacitor with a very low value (e.g. 1 pF).

There must be no coupling via the magnetic field, so the coils must be placed at a right angle.

Capacitive coupling is also useable when magnetic coupling is difficult, for instance when using ringcore or potcore coils.

# FET amplifier for measuring LC circuits.



This amplifier can be used for measurements on LC circuits.

The metal lid is removed for the photo.

The input of the amplifier is connected to the LC circuit.
The amplifiers input has the following properties:

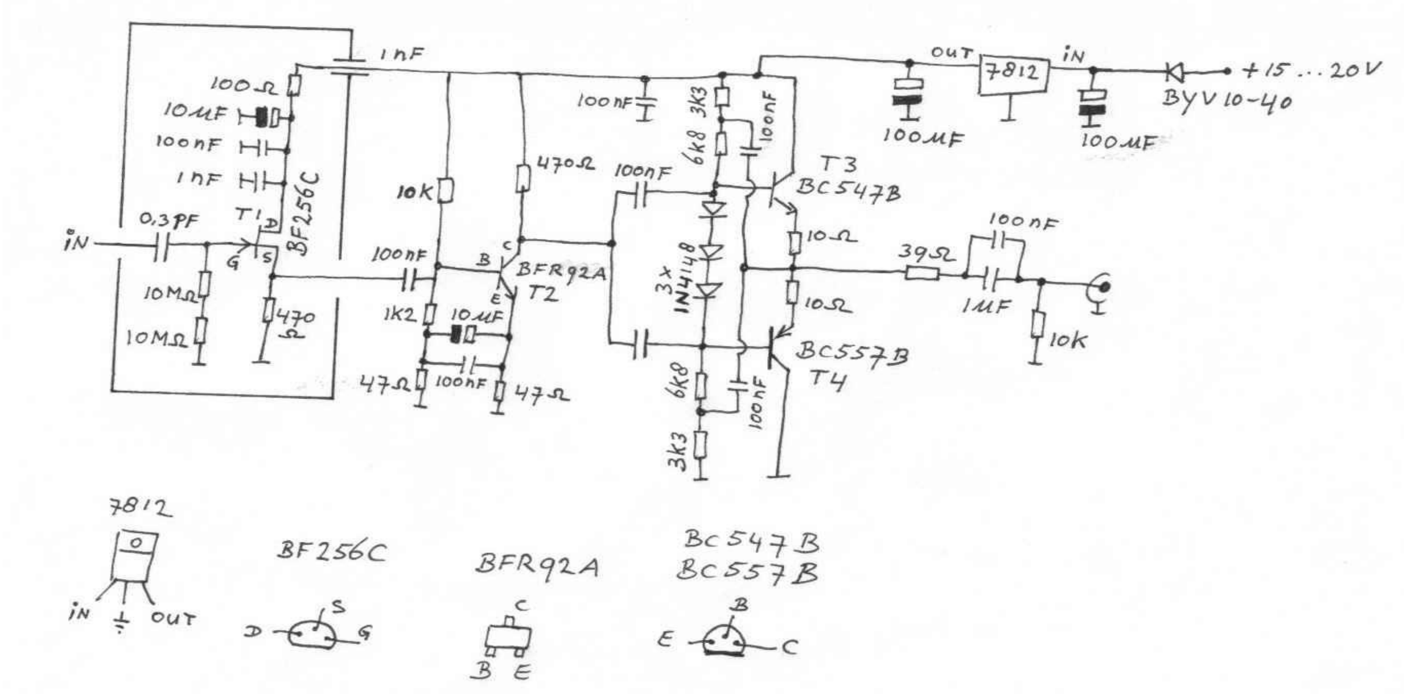
a- High input resistance.
b- Low input capacitance (about 1.4 pF).
c- Low dielectric losses, because of the use of high quality insulation materials.

Because of this properties, the LC circuit is almost not loaded by the amplifier, so the Q will almost not reduce.

The output resistance of the amplifier is 50 Ohm.
If the amplifier output is not loaded, for instance it is connented to a 1 Mega Ohm oscilloscope input, then the amplifier gain is 1x, and the maximum output voltage is 8 Volt peak-peak.
If the output is loaded with 50 Ohm, then the gain is 0.5x and the maximal output voltage is 4 Volt peak-peak.
The gain is constant between 10 kHz and (at least) 10 MHz.

The amplifier output can e.g. be connected to:

- a oscilloscope
- a RF Voltmeter
- a RF Wattmeter
- Diode detector with voltmeter



# Ampifier description:

The input signal enters the amplifier via a 0.3 pF input capacitor, toghether with the input capacitance of the FET (T1) this forms a voltage divider, the input signal is attenuated 17 times by this divider.

The 0.3 pF input capacitor is selfmade of two copperplates of 1 square cm at a distance of 3 mm.
By changing the distance between the plates we can adjust the gain of the amplifier.
The plates must have at least 1 cm distance from the surrounding grounded box.

The input signal enters the box via a 1mm copperwire, through a 10 hole in the box.
The wire is supported by a piece of polyethene, which is fixed with nylon screws.
The input amplifier (T1) is screened from the rest of the circuit.

Between the *gate* (input) of T1 and ground there is a 20 M.Ohm resistor.
But the input resistance of the amplifier is much higher then 20 M.Ohm, in theorie even $17^2$ times higher (so, 5780 M.Ohm), this is because over the 20 M.Ohm resistor is only 1/17th part of the input voltage.
In practice the input resistance will be lower then 5780 M.Ohm because of dielectric losses e.g. in the gate of the FET.

Transistor T2 is set to a gain of 17 times.
Or to be more precise -17 times, because this transistor is inverting the signal, but this is for the rest not important.
On the collector of T2 the amplitude is the same as the input amplitude of the amplifier.
The DC voltage on the collector of T2 must be about 6 to 7 Volt, if it is outside this range adjust the value of the 1K2 resistor at the base of T2.
T2 (BFR92A) is a very fast transistor (up to 5GHz) in SMD case, because of the high speed, T2 can give parasitic oscillation.
If this happens you better use a slower transistor like the BF199 (up to 500 MHz).

T3 and T4 form a buffer amplifier with a gain of 1x.
The amplifier is capable of driving a 50 Ohm load.

## Measuring the Q of LC circuits.

In theory we can determine the Q of a circuit as follows:

**Step 1**
Couple a RF signal generator to the LC circuit.
The coupling between generator and LC circuit must be loose, otherwise the output resistance of the generator will load the circuit and reduces the Q.

**Step 2**:
Set the generator to the frequency at which you want to measure the Q.
Adjust the LC circuit (turn the tuner capacitor) so you have maximum voltage over the circuit, the circuit is now in resonance, this frequency is the resonance frequency of the circuit (f.res).

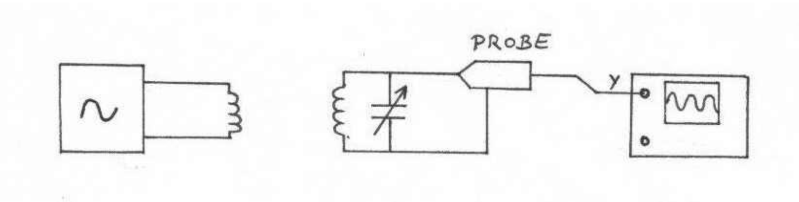
**Step 3**:
Measure the voltage over the LC circuit at resonance frequency (f.res).

**Step 4**:
Vary the generator frequency a little above and below f.res. and determine the two frequenties were the voltage over the circuit is 0.707 times the value at f.res.
The voltage reduction to 0.707 times, is the -3 dB point.
One -3 dB point, is lower in frequency then f.res, this frequency we call: fl.
The other -3 dB point is higher in frequency then f.res, this frequency we call: fh.

**Step 5**:
Calculate the bandwidth BW: **BW= fh - fl.**
Calculate the Q: **Q= f.res / BW**

For performing these 5 steps, we can use the following test setup's:

**Test setup 1** Measuring the Q with a signal generator and a probe.



In the schematic above you see from left to right the following components.
A signal generator
A coupling coil
The LC circuit
A 1:100 oscilloscope probe
A oscilloscope

Connect the output of the signal generator to the coupling coil having e.g. 50 turns.
Place the coupling coil at about 20 cm from the coil of the LC circuit.
The coupling coil don't have to be high Q.
Because of the 20 cm distance, there is a loose coupling between the coils.

Connect the probe to the LC circuit.
The earth connection of the probe must be connected to the housing of the tuner capacitor.
The probe is connected to the oscilloscope.
The probe provides a small loading of the circuit, so the Q will not reduce so much.
There are also 1:1 and 1:10 probe's, but these will load the LC circuit too much.
The 1:100 probe I use has a input resistance of 100 M.Ohm, and a input capacity of 4 pF.

The output voltage of the generator must be set so high, that the oscilloscoop gives a clear picture of the RF signal.
Because the 100 times attenuation in the probe, the signal generator output must be set fairly high.
When measuring low Q circuits, I must set the generator output to it's maximum of 20 Volt peak-peak.

For measuring the Q: perform the 5 steps described on the top of this page.

The frequency adjustment is done by hand, by turning the frequency knob of the generator.

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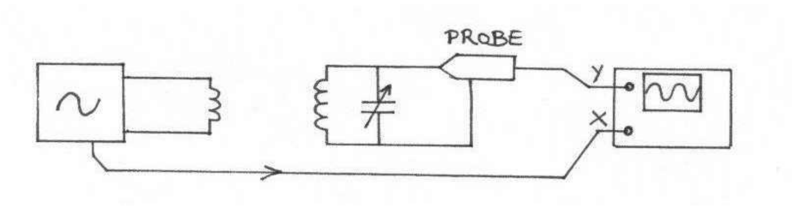
**Test setup 2** Measuring the Q with a sweep generator and a probe.



In this schematic you see from left to right the following components:

A sweep signal generator
A coupling coil
The LC circuit
A 1:100 oscilloscope probe
A oscilloscope

This method uses a sweep generator, this is a signal generator where the frequency is constant varying between two set values.
I use a sweep function generator of brand "Hung Chang" with model number G305, it can produce signals up to 10 MHz.
It has a "sweep output" which gives a voltage going up and down with the frequency sweep.

The "sweep output" is connected with the X input of the oscilloscope, the oscilloscope is placed in the X-Y mode.
Now the lightspot on the scope runs from left to right and back over the screen, this makes a frequency scale with on the leftside the startfrequency and on the rightside the stopfrequency of the sweep generator.
The sweepfrequency must be set at about 10 Hertz, this means the frequency is running 10 times per second from startfrequency to stopfrequency and back.

The Y input of the oscilloscope is connected via the 1:100 probe with the LC circuit.

The RF output of the sweep generator is connected to the coupling coil, which is placed about 20 cm from the coil of the LC circuit.

At the top: the sweep signal generator.

Under: oscilloscope with the curve of the LC circuit on the screen.

We can turn the tuner capacitor and get the curve of the LC circuit on the oscilloscope screen.
Adjust with the amplitudeknob of the sweep generator the hight of the peak of the curve to 2.83 cm.
(The peak-peak distance is then: 2x2.83=5.66 cm).

Determine the width of the curve at 2 cm high, this is the -3 dB point (because 2.83x0.707= 2).

Calculate the bandwidth:
**BW= (stopfrequency-startfrequency) x curve width at -3 dB / total screenwidth.**

And the Q:
**Q= f.res / BW**

The great advantage of this method is that changes in resonance frequency of the LC circuit, can direct be seen on the screen.
Also changes in Q can direct be seen, because the hight of the peak will change then.
At high Q circuits, we can see the hight of the peak halve for instance, when we touch the (insulated) litzwire with our fingers.

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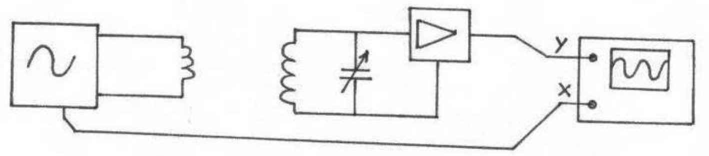
**Test setup 3** measuring the Q with a sweep generator and a amplifier.



In this schematic we see from left to right the following components:

A sweep signal generator
A coupling coil
The LC circuit
A amplifier
A oscilloscope

When using a 1:100 probe between LC circuit and oscilloscope there are two problems:

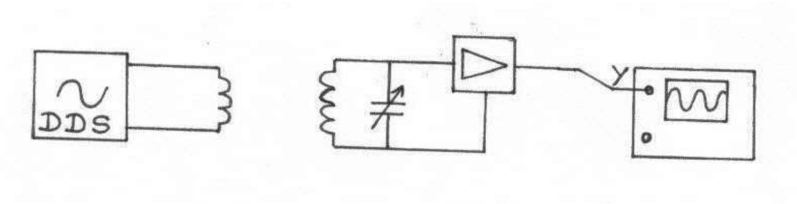
a- Because the 100 times attenuation of the signal, the amplitude on the oscilloscope will often have a very low level.
b- The probe can give dielectric losses, which reduces the Q.

To solve these two problems, I replaced the probe by a selfmade amplifier with a gain of 1x.
The amplitude on the oscilloscope will now be 100 times higher then with the 1:100 probe.
The input of the amplifier uses a FET (Field Effect Transistor) and a capacitive voltage divider, which will load the circuit only very little.

A complete schematic of the amplifier you will find here

For the rest, this test setup is the same as test setup 2.

**test setup 4** Measuring the Q with a DDS signal generator and a amplifier.



In this schematic you see from left to right:

A DDS signal generator
A coupling coil
The LC circuit
A amplifier
A oscilloscope

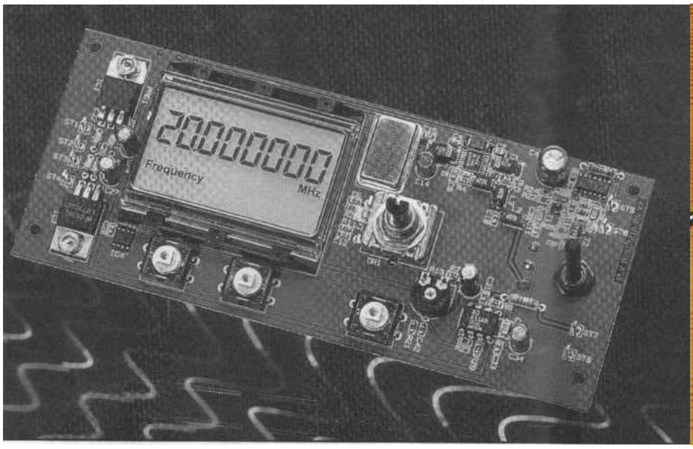
DDS means "*Direct Digital Synthesis*".

The output signal is in a DDS generator made in a digital way.
The great advantage of this kind of generator is the accuracy of the frequency setting.
The output has also a very low distortion.
The DDS generator I use, is a build yourself electronic kit from the company ELV .
You can also buy a complete build and tested module.

The specification are:

Output frequency: 0.1--20 MHz.
Output voltage: 0 -- 4 Volt peak peak (not loaded).
Output impedance: 50 Ohm.
Minimum stepsize of frequency setting is 0.1 Hz. (up to 10 MHz output frequency).
Minimum stepsize of frequency setting is 1 Hz. (10 to 20 MHz output frequency).

As stepsize you can also select, e.g. 10 Hz, 100 Hz, 1 KHz, etc.



Circuit board of the DDS generator.

DDS Generator build in a box.

I now use the DDS generator because the used sweep generator could not be set accurate enough on frequency.
And also the frequency changes slightly during the measurement.

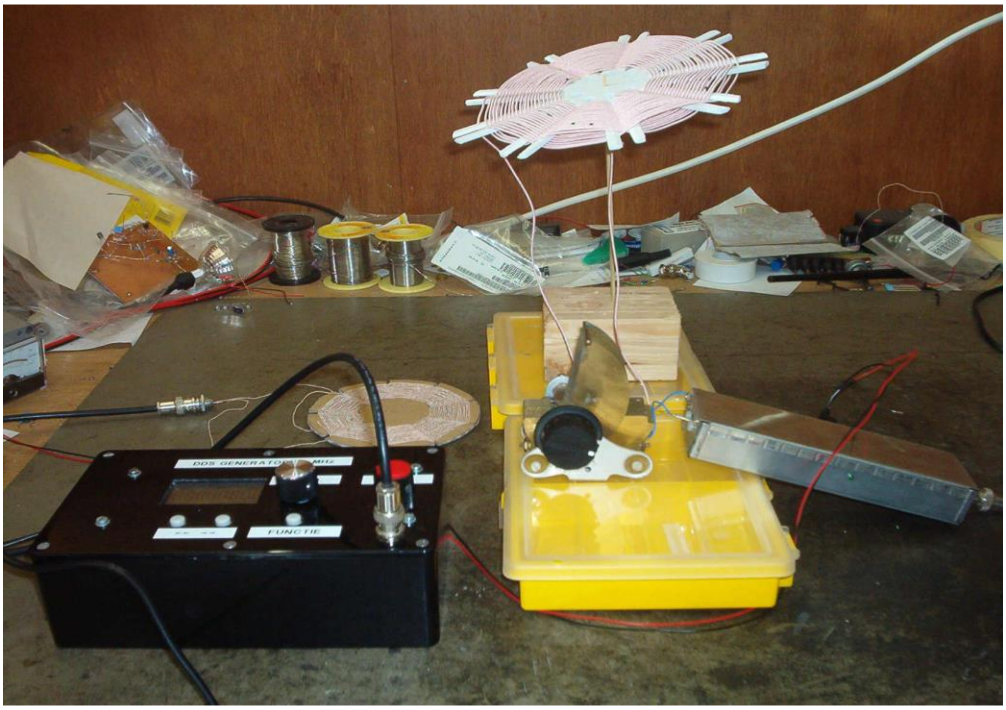


Photo of the test setup.
The coil laying on the table is the coupling coil.
The FET amplifier is connected via short wires to the tuner capacitor.
The coil of the LC circuit is placed at the top of a wooden stick, so it has not much influence from surrounding obstacles.

The windings are laying in a horizontal plane, so the coil picks up less signal from radiostations which can influence the measurement.

During measurements on high Q circuits, I tune the DDS generator in 10 Hz steps.
This test setup is in my opinion very reliable for determining the circuit Q.

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**Tips for measuring the Q:**

During measurements don't come with your hands too close to the LC circuit, because this has influence on frequency and Q.
Keep a minimum distance of 20 cm.

Don't lay the coil of the LC circuit during measurement on the table, but keep a minimum distance of 20 cm from wooden or metal objects.