The New 3496Hz Class-E Beacon and loop antenna Designs

For use with the DQ Receivers

The big change, made in 2008, is the beacon transmitter circuit board, which is a completely different design. The old parallel-tuned beacon design, which was technically a Class-E amplifier with one inductor and one capacitor, has several problems:

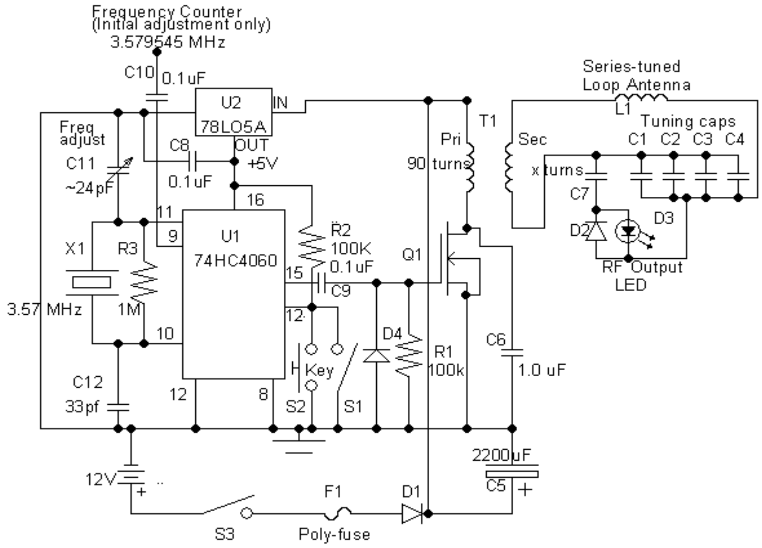
1. DC current (and heat dissipation) rises rapidly whenever the loop antenna is not precisely tuned to resonance. This can happen during initial tuning; failure of a tuning capacitor; or simply by setting the loop antenna close to a large metal object.
2. The 1/16 duty cycle causes large transients that must be absorbed by the zener diode, causing power loss.
3. The transients reach the battery, despite the large electrolytic capacitor. The circuit will function properly only on low-impedance batteries such as NiCad, NiMH, or sealed lead acid. This circuit will not function properly on "Lab" type power supplies, even supplies rated at several Amps.

The new Class-E design is derived from Mark Mallory's classic article found here. It uses square wave drive, has no large transients, is simpler, and will work on any power source. Technically it is a Class-E amplifier with two inductors and two capacitors. The impedances of the series-tuned loop antennas rise when they are de-tuned, which causes DC current to drop. The loss in the MOSFET is so low that no heat sink is necessary. The circuit efficiency is above 90%. Different series-tuned loop impedances, power levels, and DC supply voltages can be accommodated by changing the number of turns on the secondary (link) winding on a toroid. For more on this circuit design see my article in Speleonics 25, June 2005, pages 10-12; http://caves.org/section/commelect/spelonic.html .

Note that I will sell this PC board separately for $9.00 US plus postage with toroid and wire.

To assemble the 2008 Class-E Beacon board, first install all of the parts that are not involved in tuning. Refer to the parts list below. Mount R1, R2, R3, C5, C6, C7, C8, C9, C10, C12, D1, D2, D4, F1, U1's socket, U2, and X1. Note that U2 is installed with its semicircular side facing to the right in the parts layout diagram below. D3 must be installed with the correct polarity (opposite to the polarity of D2). Note that Q1 is specified as an insulated tab MOSFET. Also note that it is a "logic level" gate type that turns on at only 2-3 volts. Ordinary MOSFETS may not fully turn on at 5VDC gate voltage and may heat up! Q1 is mounted with a 4-40 screw or the metric equivalent. A MOSFET with a bare metal tab must use insulating hardware to isolate it from the PC board!, but heat sink compound is useful. I have a few of the original Q1 MOSFETs available for $2.00 US each, which should be ordered with the beacon board or 3-part DQ board to save postage.

There are 3 choices for C11, which adjusts the frequency of the crystal oscillator. The frequency is only critical if this beacon will be used with other peoples DQ receivers that have the digital field strength readout, or if you own more than one beacon. In either case, the frequency should be set precisely to 3.579545 MHz to match the other beacons using Test Point 1 (**TP1**) and a good frequency counter. I use a x10 scope probe to avoid loading down TP1. The easiest tuning method is to install a 6-50pF trimmer in either C11 position. I strongly recommend measuring the trimmer's value, then installing fixed COG (NPO) ceramic capacitors in its place. The trimmer's value will shift with time and handling. If this beacon will only be used with your receiver, and especially if the receiver does not have the digital readout, C11 can be a common 27pf 10% ceramic cap. A 24pf 5% cap will usually be very close to the correct frequency.



TRANSMITTER CIRCUIT DIAGRAM

NOTES: 1) Strictly speaking, the exact frequency 3495.65 Hz) is not important as long as it matches the receiver.
If you will use only this one beacon with your receiver, then C11 can be a 27pF fixed cap.
If you have two transmitters, however, or you will use other people's beacons you need to standardise on the 3.579545 MHz crystal frequency, which is divided by 1024 to give 3495.65 Hz beacon freq.
C11 should be replaced with a fixed capacitor once the correct value is found.

2) F1 and D1 are optional for protection and reverse voltage protection.

3) S1 is a SPST switch to hold transmitter on for continuous measurements.
S2 is a momentary action pushbutton for morse code.
S1 & S2 can be replaced by a jumper wire (and R2 deleted). S3 will then turn the beacon on/off
Alternatively, because idle drain is so low, S3 can be deleted and the battery connected for the day's use.

4) The beacon can be keyed on/off by an external source such as a timer or pulser by connecting 5V CMOS logic to pin 12 (deleting S2 & R2).

5) D3 will light up only when a signal is actually being transmitted. Change C7 to adjust brightness.

6) U2 must be deleted and bypassed if the beacon is re-designed for operation on 5 or 6 VDC

7) See assembly instructions for info on winding T1 & L1 and tune-up.
The number of turns on the secondary of T1 will vary with the loop antenna chosen and the power level desired. The secondary winding is typically 15-25 turns. See text.

Title		
New Class-E Beacon Schematic		
Author		
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File		Document
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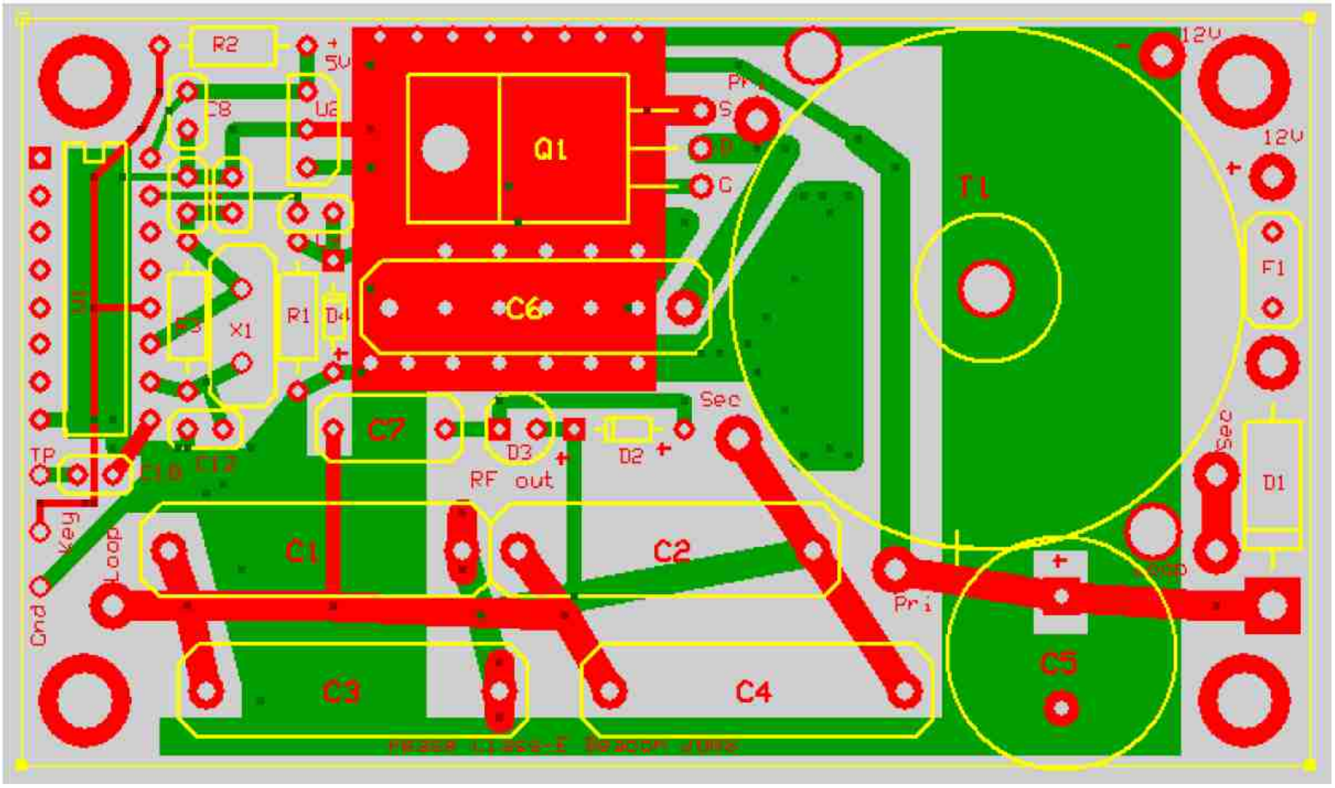
Revision	Date	Sheets
1.1	2/18/08	1 of 1

2010 (Current Style) CLASS-E BEACON PARTS LIST

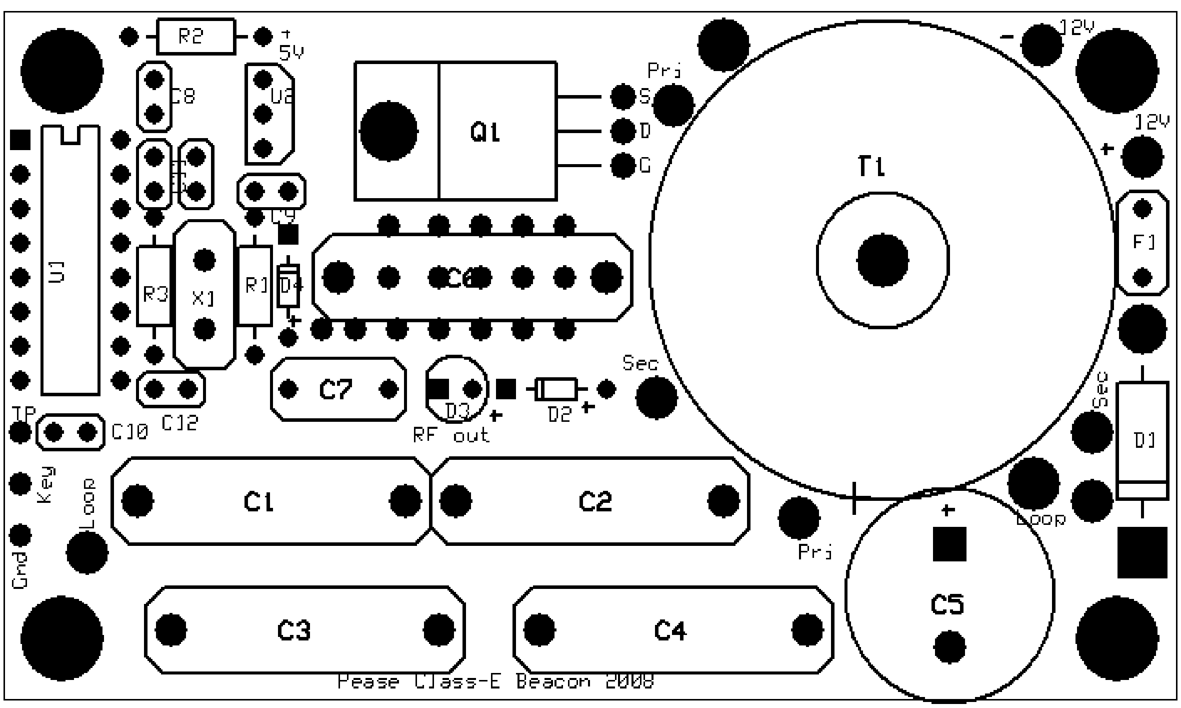
The part numbers are a moving target, but the online catalogs work well.

PART NUMBER	Value (and if Mouser part)	Part no. (DigiKey=ND)	Price each or/qty
R1, R2	100K 1/4w carbon film	100KQBK-ND	.27/5
R3	1.0M " " "	1.0MQBK-ND	.27/5
C1, C2, C3, C4	250VDC Polypropylene caps	selected to tune loop L1	see text
C5	2200uF 25V electrolytic	P10285-ND	1.61
C6	1uF 63V polypro	BC2076-ND	1.48
C7	.0047 250V polypro	495-1281-ND	.43
C8, C9, C10	0.1uF ceramic	399-4209-ND	.16 or 1.21/10
C11	6-50pF trimmer	490-3750-ND	.93
C11(fixed sub for C11)	27pF ceramic	490-3715-ND	.32
C12	33pF ceramic	490-3726-ND	.28
D1	5A 30V Schottky diode	SR503DICT-ND	.92
D2, D4	1N4148 switching diode	568-1360-1-ND	.04 or .68/25
D3	T1 green diffused LED	160-1142-ND	.19 or 1.45/10
F1	Poly fuse, 1.6A hold	RUEF160-ND	.46
L1	Loop antenna, see text		
Q1(MOSFET)**	Ron=.022 Ohms, 55V, 30A	IRLIZ44NPBF-ND	2.73
Q1(Alternate)**	Ron=.028 Ohms, 60V, 30A	IRLIOZ44GPBF-ND	3.08
T1	1242uH Primary Winding, 90T of #20 on toroid	CWS Bytemark CM-270-125	3.00 (supplied with PC board)
U1	74HC4060 Osc/Divider IC	MM74HC4060N	.68
U2	5V Regulator, TO-92	MC78L05BP-APMSCT-ND	.20
X1	3.579545 MHz crystal, 17pF	X049-ND	.40 OR 3.60/10

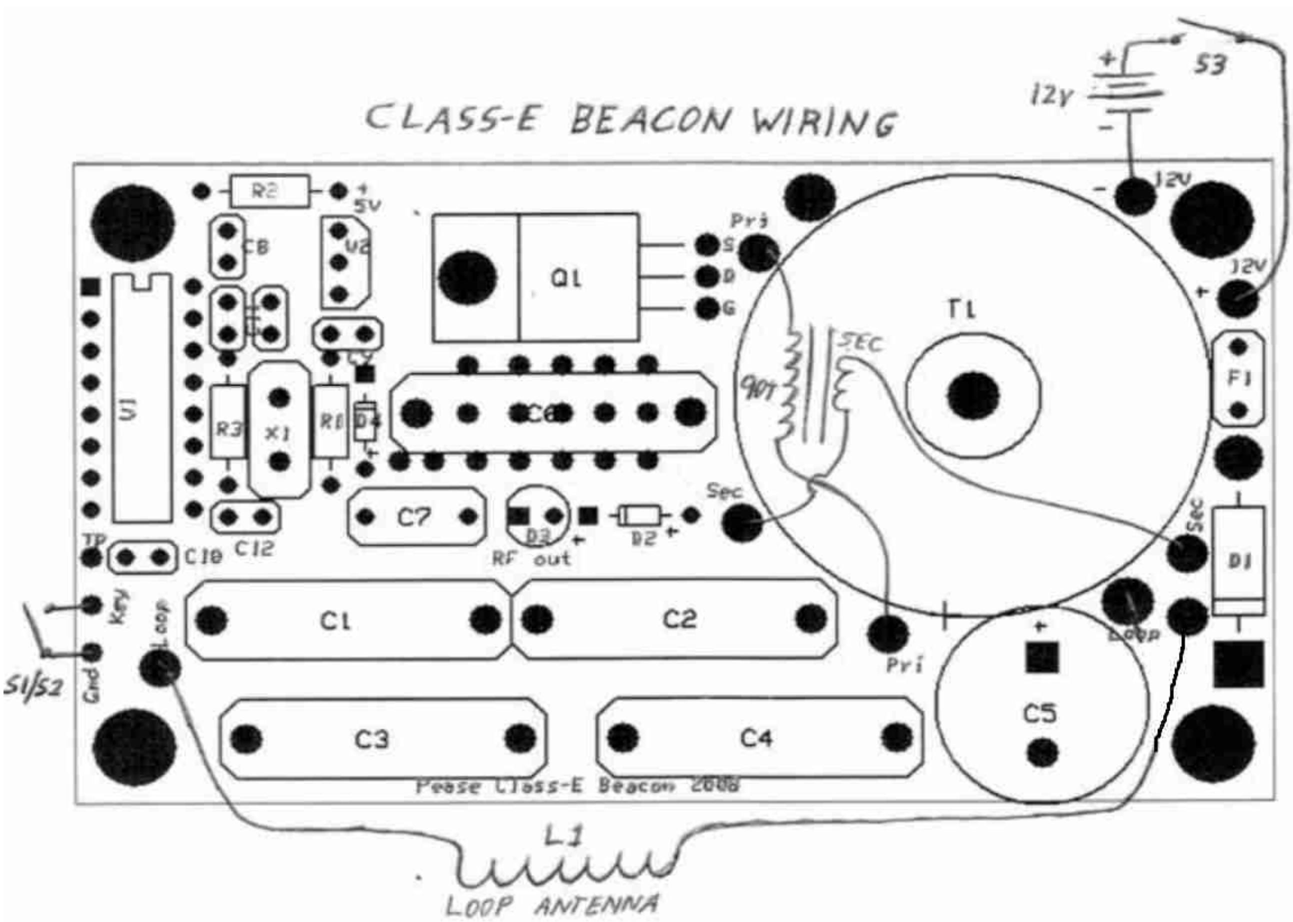
** These insulated case, logic level gate drive, MOSFETs are no longer being manufactured and may not be available. Substitutes will not have the "fulpac" insulated case and will require an insulating kit. I have a few IRLIZ44NBPF-ND in stock for $2.00 each plus shipping.



Class-E Beacon PC Board



Class-E Beacon Parts Layout



New info (Apr 2020): The circuit shown is optimized to draw 7 Watts from a 12V AGM battery. It is OK to run up to ~10W and down to 1W or less by varying the number of turns on the secondary winding. The battery could be as low as 8 Volts. There are 90 turns on the primary of T1 (~1242uh), and C6 is 1uf. The idle loss (no antenna connected) is ~25ma (0.3W).

For higher power use, with a 13V Lithium Iron Phosphate battery, wind 58 turns for the primary of T1 (~565uh) and change C6 to 2.2uf, which is the next larger standard value. This is optimized for 17.8 Watts. It is OK to run up to 20-25W and down to 1W. The MOSFET will get warm to the touch at 25W. The penalty is that the idle current loss is 42ma (0.54W).

It can be useful to put taps on the secondary winding to trade off signal strength for run time. For example, I have 3 power levels on my 5ft diameter beacon that uses a 10AH LiFePo4 battery. Assuming 8AH available, I will get 67 hours at 1.5W, 13 hours at 7.8W, and 3.8 hours at 27W (which is pushing the circuit!).

Once you have tuned your loop at one power level, it is easy to calculate the secondary turns for othert power levels. Power is proportional to the square of the ratio of the turns. For example, to double the power, you would increase turns by sqrt 2 = 1.4 times.

Wind the Primary of toroid T1 (provided) with 90 turns of #20 wire (provided). This is the longer length of smaller wire. Start by feeding half of the length of wire through the center of the toroid core.

Now wind one half of the wire onto the core, counting turns. Wind a compact even layer. The easiest technique is to feed a loop through the center hole, then insert a finger into the loop and pull the length of wire through the hole. This is much faster than feeding the wire end into the hole because the wire tends to tangle. The second half will overlap into a second layer, which can be spread out evenly. It is a good idea to leave one lead long (for now) just in case. This will give close to 1242 uH, which is the correct value when C6 is 1uF. Note that these values of L and C deliberately do not resonate exactly on 3496 Hz even though they form a broadly tuned "tank" circuit. C6 is shorted out for half of each carrier cycle. These values are adequate for power levels from 1 Watt up to 10 Watts or so. See the article in Speleonics 25 mentioned above. This winding connects to the two large "pri" holes on the board.

The secondary (link) winding, which feeds the loop antenna, is wound over the top of the primary winding with the shorter length of larger #18 wire, spreading the winding more or less evenly around the toroid. The number of turns required depends on the particular loop antenna chosen; the power level desired; and the battery voltage chosen. The number of turns could vary (typically) from 15 to 25, less for very low power beacons. The smaller number of turns is associated with loops with lower series-resonant resistance, and/or lower power levels. It is easy to tap this winding to allow two or more power levels. The trick is to initially leave a long lead (as much as 1 ft [0.3m]) on one end to allow the easy addition of turns during tune up by unsoldering a single wire. This winding connects to the two "sec" holes on the board

Later, once the beacon is tuned and working properly, T1 can be secured to the board with silicon rubber and one or two tie wraps.

Tune Up

The first step in tuneup is to apply DC power to the board with the key switch closed (ON), no loop antenna connected, and an ammeter in series with the battery. The circuit should draw a low current. My breadboard drew 25 mA (.025 Amps) but will vary from as little as 18mA. A high current indicates that either C6 or the primary of T1 are the wrong value. A current close to zero indicates that the power MOSFET is not getting its gate drive, which should be a 5 Volt 3496 Hz square wave on the "G" pin. Check the operation of the 3.57 MHz oscillator.

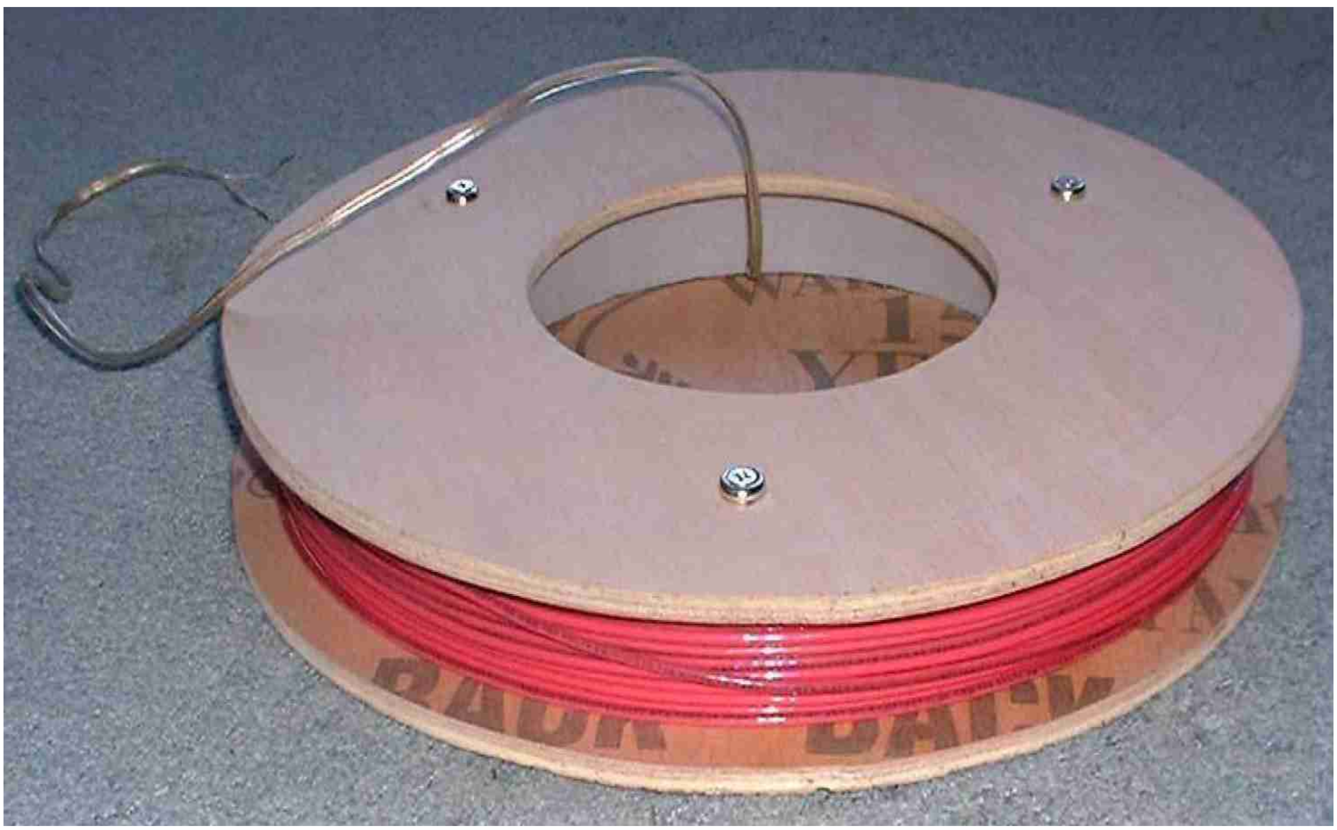
Capacitors C1-C4 are all wired in parallel to series-tune the loop antenna. Often, only one or two capacitors are necessary. Polypropylene capacitors should be used for C1-C4 because they are much lower loss than the smaller (and cheaper) polyester (Mylar) capacitors. If additional small capacitors are needed for precise tuning, they can be be mounted between C1-C4, or under the board. These small capacitors could be polyester because they are such a small part of the total value. A 250 VDC rating is adequate for most wire loops, and for all of the examples given here. Higher Q loops or higher power levels may require a higher voltage rating, up to 600VDC. A capacitor decade box is very useful here. The tuning procedure is to adjust the C1-C4 value to maximize battery current drain and/or AC loop voltage, both of which will occur at the same value of capacitance, or very close to it. Record the final value of DC current. There is no danger of overheating the circuit unless the power level is very high (15-20 Watts). The next section gives several examples of actual loop antennas that were tuned up using a breadboard version of this beacon circuit.

NOTE: Prior to each use of a beacon, it is wise to connect it to the battery and measure the DC current drain to make certain that the tuning is still OK. If the DC current is more than 10-20% lower than the value recorded when the beacon was initially tuned, the tuning should be checked.

Examples of Antennas for the New Beacon Design

This section describes several actual beacon antennas followed by a table giving approximate tuning capacitor values and the number of turns on the link winding for different power levels and operating voltages. All values are only approximate for loops that you wind. In particular, the actual PC board should give higher output power and DC current than the breadboard, which had some thin wiring and several clip-lead connections. All of the loops are wound with wire available at Home Depot, Lowes, or electrical wholesalers. It is insulated, solid or stranded (as indicated), THHN rated, on 500 ft spools. Unfortunately the cost of copper has doubled recently. Currently, a 500 ft roll of #14 solid THHN is $30.00 US while stranded is $35.00. For those outside of the US, #14 bare copper wire is about 1.65 mm dia. and #12 is about 2.05 mm dia.. Feedlines for all of the antennas can be 2-conductor appliance power cord, or the loop wire can be extended and twisted together. I use a few feet of rubber-covered cord with wires of at least #16 (1.3 mm dia.). Because I plan to mount the beacon electronics in the center of the smallest loop, I fed the loop with a piece of loudspeaker wire, which is acceptable in such a short length.

The first antenna is a small wire loop. The winding is 50 turns of #14 stranded THHN wire (could be solid wire) wound on a rigid form 12" (30.5 cm) in diameter and 1.25" (3.2 cm) wide. Inductance is 1.419 mH for my loop. The loop form is 14" (35.5 cm) dia.. The "filler" ring is some scrap stiff closed-cell foam. A bubble level is installed in the form. Remember that this is just an example. The dimensions are only critical if you wish to make an exact duplicate. There is plenty of room to wind more turns or to use larger wire. This loop is suitable for locations up to perhaps 250 ft (75 m) deep at 7W power.



12 Inch Loop

The next antenna is 37 turns of #12 solid THHN wire which was initally wound on a plywood wheel which had a circle of nails 22" (56 cm) in dia.. The resulting winding was tightly tie-wrapped every few inches before removing it from the wheel. The inductance is 1.802 mH. The loop is rigid enough to be used by itself without a frame, making it the easiest to construct, cheap, and lightweight for its very strong signal. It can be covered with duct tape or other material to make it even more rugged. It can be made even more rigid by wrapping narrow fiberglass sailboat batten material around its perimeter. The only drawback is the need to carry a line level on a string to level it. Line levels are ~$2.00 at Home Depot. This antenna will easily do locations 300-400 ft (90-120 m) deep with 7W power.

22 Inch Loop

The largest antenna is a flexible 5 ft diameter (1.52m) loop with an external hexagonal folding frame. It consists of 20 turns of #14 THHN stranded wire that was wound around 6 metal spikes placed in a 5 foot diameter circle in my lawn. Tie wraps were placed where the 6 arms of the frame would later go, then the entire loop was tightly wrapped with plastic electrical tape to stabilize the inductance (1.92mh) and provide some protection. On this frame, it tuned with 1.068uf. I tapped the secondary winding at 4, 10, and 22 turns for 1.5, 7.8, and 27 Watts with a 13V battery. It can be "figure-eighted" twice to fit in a cave pack.

The frame shown was repurposed for this larger loop by adding couplings to the ends of each arm, and making one arm slightly longer to pull the loop tight with a hook. Aluminum wire was used for the hook and inserts, with shock cord used to hold the loop in place to allow assembly by one caver. A line level on a string is required to set this loop level. This loop can easily do 600ft (183m) deep locations.

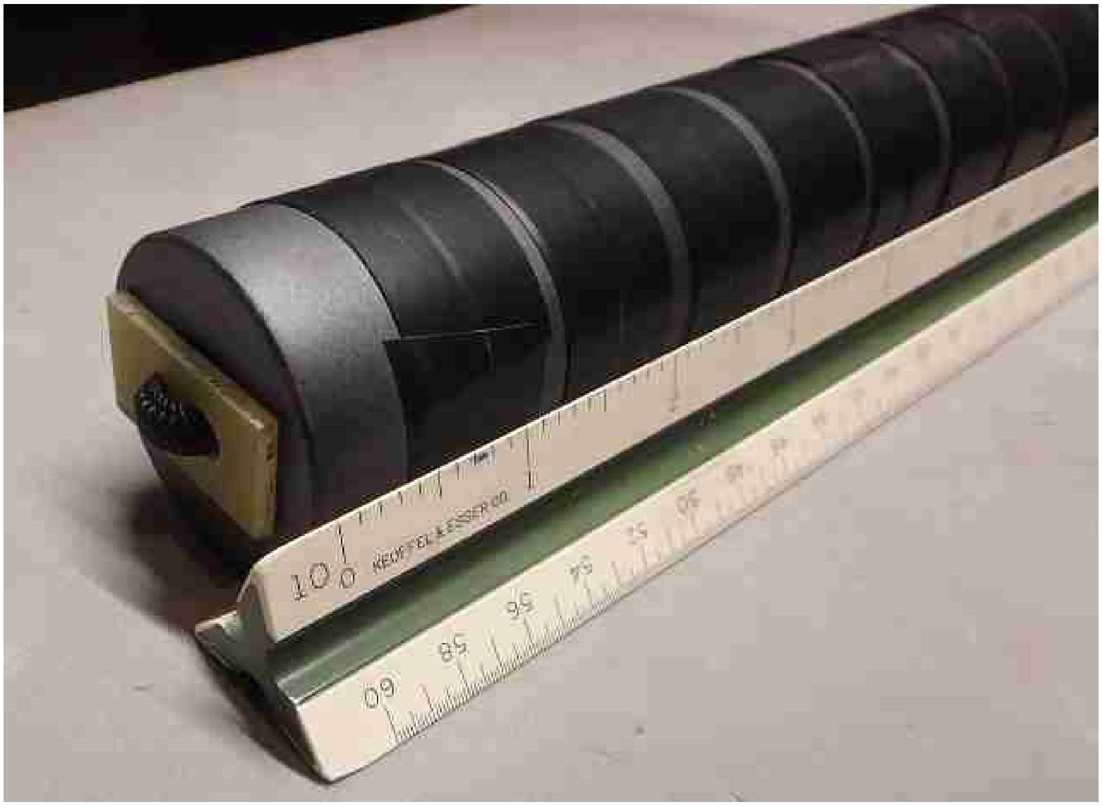
5 ft diameter loop

Ferrite Rod Loops

I have finally found a good ferrite core to construct large (heavy, 4 oz each!) rods with, that can handle reasonable transmit power and is inexpensive. It is the Fair-Rite 2643251002 EMI suppressor core pictured below. Mouser sells these for $3.08 US each in quantity of 10 or more. It is perfectly flat sided for stacking and is not plagued by "bistable" operation while transmitting normal beacon power levels. I built a 10-core rod by taping the cores together with electric tape and threading shock cord through the center to hold them tightly together. I slid the rod into 1.5" ID PVC pipe using extra tape to shim for a perfect fit. The winding is 163 turns of #14 THHN stranded wire in 2 layers. I used 2.5" ID pipe for the outer case with #16 power cord for the feedline.

10-Core Ferrite Rod loop Antenna, 15” (38cm) long

Antenna before assembly



The 10-Core stack with tape and bungee cord

A single Fair-Rite 2643251002 ferrite suppressor core of 43 material (u=800) 1.5” dia by 0.85” high

A self-leveling rod antenna such as this can be carried by cave divers, whose position can be tracked from the surface, in effect mapping the submerged cave from the surface. I have actually tracked divers in urban Tampa Florida and in other Florida springs at depths of more than 200 feet (60m). This antenna weighs 7 lbs (3.2kg) in air and would need floatation for divers to carry. It can be set up quickly in dry caves by hanging from a natural point or with a tripod of small PVC pipe.

Stan Sides has built a compact 5-core rod antenna by gluing the cores in a stack with JB Weld, a filled 2-part epoxy. This allowed winding 68 turns (~34ft) of #14 THHN stranded wire in 2 layers

directly on the core, which is then shimmed with electric tape to slide into smaller 2” PVC pipe. My antenna would be much smaller if built this way.

He used a thin layer of JB Weld (allowing 2 days to cure well) to put the 5 cores together, which allowed him to put 68 turns of #14 stranded THHN wire directly on the cores (34’ of wire).

He used epoxy to fix nylon ties at the top and bottom to serve as winding stops. In this photo the black tape is to help hold the assembly tighter in the 2” PVC tube.
Inductance was 620.2 microHenries (0.6202 milliHenries) so it will need 3.3 microFarads or less to resonate at 3496 Hz. X(L) is 13.6 Ohms. All his beacon caps are 630 VDC. He started with 19 turns on T1 secondary and adjusted turns to his desired power level.

One thing to keep in mind is that ferrite is a brittle ceramic that can shatter easily if the antenna is dropped (ask how I know!). I use closed cell foam inside both ends of the outer case, plus a foam pad taped to the bottom.

Loop Antenna (see above)	Tuning cap, uF	Vdc Volts	Idc * Amps	Pin * Watts	Link Turns	Loop V * Volts RMS	Loop I * Amps RMS	Magnetic Mom * A-T-m sq	Weight Lbs/kg
12" loop 50 turns	1.456 uF	12.7 V	0.92 A	11.7 W	17	135 V	4.33 A	18.5 A-T-m sq	4/1.8
12" loop 50 turns	1.456	12.7	0.72	9.1	15	120	3.85	16.5	
12" loop 50 turns	1.456	~6V AA	0.32	1.9	15	54	1.73	7.4	
22" loop 37 turns	1.141	12.7	0.85	10.8	19	142	3.59	35.6	5.8/2.6
22" loop 37 turns	1.138	12.7	0.55	7.0	15	120	3.03	30.0	
22" loop 37 turns	1.138	~6V AA	0.24	1.4	15	52	1.31	12.9	
5ft loop 20 turns	1.068	13	2.1	27.3**	22	200	4.8	175	5.8/2.6
5ft loop 20 turns	1.068	13	0.6	7.8	10	121.4	2.9	105	
5ft loop 20 turns	1.068	13	0.12	1.5	4	45.4	1.08	39.3	
8.5”(core) ferrite rod, 163 turns	0.61	13	0.65	8.5	15	240	3.2	13.1	7.0/3.2
4.2”(core) ferrite rod, 68 turns	3.22	13	1.2	15.6	15	97.7	7.2	? (not meas)	Stan Sides

* NOTE: These values were measured with a breadboarded circuit and will likely be higher with the actual PC board.

** NOTE: The 5ft loop is used with the higher power beacon with 58 turn primary and 2.2uf.

Antenna Tuning Table and comparison of a few actual beacon loops with the new Class-E circuit

For those who care, a method to calculate the number of link turns needed for any antenna is given here. Note that if you adjusted your T1 winding to other than 90 turns to obtain the exact inductance, or used the 58 turn “high power” version, use that # turns instead of 90. The following calculations are for the 5th antenna from the top of the table above.

If you measure the inductance and the resonant Q of the parallel-tuned loop (ie shorting out the link), you can calculate the series-tuned resistance as just the inductive reactance/Q. For my 22" 37-turn loop I get L=0.51 + j40 Ohms, Q=78 by direct measurement. The link is loaded with ~0.51 Ohms (plus feedline resistance and a bit of cap loss). Mark Mallory's "Z" equation in Speleonics 25 gives the load impedance that the circuit should see directly on the MOSFET drain for a given supply voltage and power level.

Z=[1.2638(Vsquared)]/P

Z=load impedance at MOSFET drain, Ohms: V=battery voltage, Volts: P=battery power drain (Volts x Amps)

If we want 12.7VDC and 0.55A, as in one of my examples, then the desired load Z=29.2 Ohms (across the entire 90 turn winding). Impedance changes as the square of the turns ratio. To convert 29.2 to 0.51 ohms should take a link of sqrt(0.51/29.2) x 90=12 turns. The reality is that 0.51 Ohms is really a higher value, thus the 15 turns specified in my table.