## Chapter 6 – Baluns

So-called "baluns" are widely used in ham stations, but few hams understand how they work or what their real function is. Virtually all discussions of baluns begin by saying that a balun is used to connect balanced antennas to unbalanced transmission lines – it's like jazz coming up the river from New Orleans. While both statements contain a grain of truth, there's a lot more to both stories! This chapter is an attempt to fill that void.

In an ideal radio system, the transmission line for our antenna would act as if the transmitter (or receiver) was physically located at the feedpoint of the antenna, with nothing in between. There would be no loss, and no interaction of the feedline with the antenna. We've gotten to this point with microwave systems – indeed, all of the RF electronics for many of these systems can clamp onto the back of a dish and drive it directly. We're not there with HF (or even VHF) systems though, and not likely to get there, thanks to the power levels, wavelengths, and antenna types that are practical. So in the real world, we're stuck with transmission lines for most of our antennas. *The primary function of most baluns, at least in our ham stations, is to minimize the interaction of our antennas with the transmission lines that connect them to our radios.* So let's dive in and learn a bit more about how antennas, transmission lines, and baluns work.

Balance We should begin by defining a balanced circuit. *A balanced circuit is not defined by the equality of current or voltage on the two conductors. Rather, a balanced circuit is one in which the impedances of the two conductors to the reference plane are equal in both magnitude and phase. A balanced circuit functions as a Wheatstone bridge, rejecting noise by virtue of the balance of the impedances within that system. [There is an excellent analysis of this in Whitlock, JAES, June 1995, and also on the Jensen Transformer website.]*

Antennas and Balance We like to think of a center-fed dipole as a balanced antenna, and in an ideal world it would be. To achieve that, we would need to suspend it over perfectly flat and uniformly conducting earth, between electrically symmetrical support structures. There could be no buildings below it, no wiring, no conductive objects around it that were not perfectly symmetrical with the antenna, and the feedline would need to be perfectly perpendicular to the antenna all the way to the transmitter.

As hams, few of us are able to install anything approaching a balanced antenna. We must suspend them from metal towers, trees, or the side of building. Often the ground beneath them is not flat, there are power lines, telephone lines, and there is wiring in nearby buildings. The antenna has capacitive and inductive coupling to all conductive objects in its near field. Rarely will that coupling be symmetrical, and rarely will it be possible to quantify it. In short, even the best of our antennas are a compromise.

An example of a ham antenna that might have met that criteria of a balanced antenna was a dipole I was able to hang between two identical towers on top of the EE building at the University of Cincinnati when I was a student and trustee of W8YX in the early 60's. I used the word "might" because although the towers were mounted symmetrically on the building, one held a large beam antenna. There goes the balance!

Even with ideal ladder line feeding our real world "sort of" balanced antenna, the antenna imbalances cause the currents in the two halves of the antenna to be unbalanced (that is, unequal), so the current on two sides of our balanced feedline are not equal. The imbalance between the two currents is a common mode current, and it causes radiation from the feedline! And because all antennas work in reverse, any current flowing on the feedline couples unequally to the two sides of the antenna. The difference between those currents is sent back down the feedline as a differential signal to our receiver. That feedline current could be noise from our neighbor's battery charger, or a station coming from a direction we thought our beam antenna was rejecting.

Coaxial Feedlines and Balance A coaxial feedline can add to the imbalance that already exists in our real world antenna. Because it is the most obvious of the imbalances (although not necessarily the dominant one) it is the one that we pay the most attention to. The way we pay attention to it is by adding a lump at the feedpoint that the guy at the ham radio store tells us is a balun. It's all nicely glued into a weatherproof housing that we can't take apart without destroying it, and the data sheet tells us nothing more than how wonderful it is. So now we're back where we started, asking "*What is a balun?*" And while we're at it, perhaps we should ask how it works.

Types of Baluns There are three fundamental types of baluns, and several variations within each type. The three types are very different electrically, and they interact differently with the imbalances of both the feedline and the antenna.

Voltage Baluns A "voltage" balun is essentially a transformer, most often with a primary and one or more secondary windings on a ferrite core. The Ruthroff baluns described by the late Jerry Sevick, W2FMI, and Doug DeMaw, W1FB, and the W2AU balun sold by Unadilla, are transformers (that is, "voltage" baluns) that use ferrites as a core to carry the flux between windings.

Transmission Line Balun A balun can also take the form of a half-wavelength of transmission line (Fig 32). In the most common configuration, the center conductor of a 50 ohm line is connected directly to one side of a 100 ohm antenna and also to a half-wavelength of the same line, which in turn drives the other half of the antenna. The two sides of the antenna are thus driven in parallel, but 180 degrees out of phase with each other (but only at the frequency for which the transformer (the extra length of line) is one-half wavelength. As we move away from that frequency, the phase shift will be a bit more or a bit less. The antenna still works, but the balance degrades a bit.

Fig 32 – A Half-Wave Balun

Current Baluns First published by Guanella and pioneered by Sevick, Joe Riesert (W1JR), and Walt Maxwell (W2DU), current baluns are actually common mode chokes applied to a feedline. Current baluns see only the common mode field. When wound with coax, this is true because all of the magnetic field associated with common mode current is outside the line, while all of the field associated with the transport of power from the transmitter to the antenna is inside the coax. When wound with parallel wires, the core sees the sum of flux from currents of opposite polarity; the differential components cancel, leaving only the common mode flux (due to the imbalance in the system). Current baluns work by adding a high impedance in series with the common mode impedance of the line, thus reducing the common mode current to a very small value – if no common mode current is allowed to flow on the transmission line, the current on the left half of the antenna must be equal to the current on the right half of the antenna, simply because there is no other path for current. There are three fundamental types of current baluns.

- Solenoid Balun The coaxial line is wound into a coil at the antenna. The choking impedance is the inductance of the coil. Reisert describes several designs for solenoid baluns (see Appendix 4), and the ARRL Handbook includes several designs for solenoid baluns.
- Inductive Ferrite Choke Balun The line is wound around a toroidal ferrite core that has low loss at the frequency where the balun is used, so all (or nearly all) of the impedance is inductive. The line may be coax or it may be bifilar (parallel wires). Reisert's toroidal baluns are wound on a material like #61 that has low losses at HF (Fig 12, Fig 33). [Reisert also introduced the concept of a crossover winding style, whereby half of the choke was wound in one direction around the toroid, then crossed 180 degrees to the other side of the toroid and wound in the opposing direction. Sevick noted that he was unable to measure any effect of this technique. My measurements confirm Sevick's results.]
- Lossy Ferrite Choke Balun Maxwell introduced the concept of passing a coaxial line

through a string of lossy ferrite cores to form a common mode choke, a design which has come to be known as the W2DU balun. Maxwell's design consists of 50 Fair-Rite 2673002402 beads, 0.19" long and just big enough to fit over RG-303 coax (Fig 34). One of his experimental models used 300 beads, and measured 4500 +j3800 ohms at 4 MHz. Notice that his choke is resonant at about 8.5 MHz because that is where his #73 beads are resonant. A W2DU balun will be most effective on 40M, 30M, and 20M.

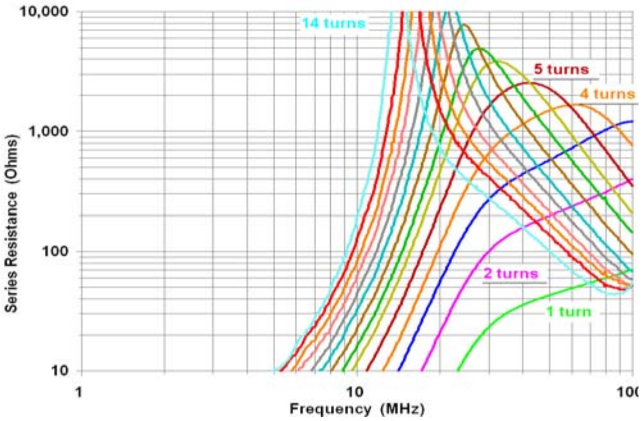


Fig 33 – $R_S$ for chokes on 2.4" o.d. Fair-Rite #61

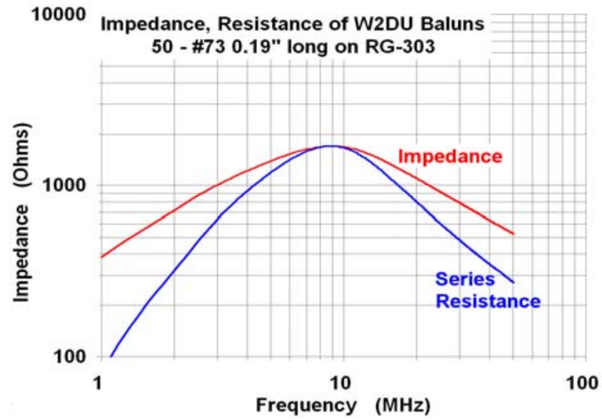


Fig 34 – A W2DU Balun (Measured Data)

Others have proposed variations of the W2DU balun without realizing the importance of resistance. Fig 35 is computed data for straight uncoiled "string of bead" choke baluns using 1.125" long #31 beads. As with all bead baluns, the impedance of a straight balun is approximately equal to the impedance of one bead multiplied by the number of beads in the string. The W0IYH balun uses 100 #43 beads, 0.562" long, 0.25" i.d. The resonance of these beads (and thus the balun) is around 150 MHz, so these baluns are strongly inductive on the HF bands! K3LR has measured them. His results suggest considerable stray capacitance, which in turn suggests either measurement error (stray capacitance is a common measurement error) or that his string of beads may be coiled (increasing stray C, lowering $F_{RES}$, and improving performance).

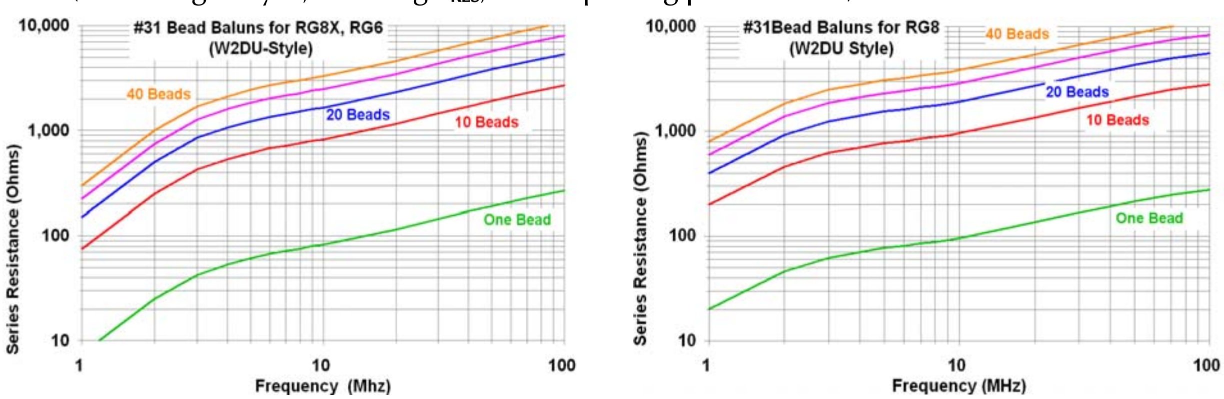


Fig 35 – Equivalent Series Resistance of #31 Bead Baluns (Computed from Fair-Rite Data)

**Advantages of Current Baluns** Maxwell seems to have been the first to realize that with a current balun, loss in the ferrite is not a bad thing if you have enough of it! (We'll discuss this in detail a little later). Maxwell, and Roy Lewallen (W7EL) showed that a current balun has some important advantages over a voltage balun, and that the advantages are so great that only current baluns should be used in most ham radio applications. [Walt Maxwell, "*Some Aspects of the Balun Problem,*" QST March 1983, http://w2du.com/r2ch21.pdf ] [Roy Lewallen, W7EL, "*Baluns: What They Do and How They Do It,*" http://www.eznec.com/Amateur/Articles/Baluns.pdf ] The ARRL Antenna Compendium Vol 1] Let's look at those advantages.

- Because the core sees only the common mode flux, a much smaller ferrite core is needed to handle high power without saturation.
- If the common mode impedance is high enough, common mode current can be forced to

near zero, which in turn forces near ideal balance.

Disadvantages of "String of Bead" Baluns The common mode (choking) impedance is the impedance of one bead multiplied by the number of beads. As a result,

- 1) We are stuck with the resonant frequency of the bead used in the string. If the bead is inductive, the choke will be inductive, and nearly all commonly available beads are inductive in the HF spectrum. The exception is Fair-Rite #73 (see Fig 34), and the largest cable that fits through the largest #73 bead is RG-303.
- 2) As Figs 34 and 35 show, it takes a very large number of beads to achieve even modest choking impedance. The usual compromise is using too few beads, which results in insufficient choking impedance. The resulting common mode current can overheat the balun, often to the point of failure, and couple RX noise.
- 3) This is a very inefficient use of the ferrite material.

Disadvantages of Voltage Baluns The ferrite core of a transformer balun (the Ruthroff "voltage balun") sees all of the transmitted power, so it is easily overheated and saturated by high power. Because voltage baluns are carrying the entire transmitted signal, they should not be allowed to saturate, because that would create both harmonic distortion and intermodulation distortion. You will be quite unpopular on the ham bands if you do either, and you will be quite likely to do so if you run high power through a voltage balun unless it is a very large one. ***This leads to the first two big negatives for voltage baluns – they must be large to handle power, and they can generate both harmonics and splatter if they are overloaded***.

Related to these negatives are two important design constraints – ***the cores of voltage baluns must have relatively low loss, and they need fairly high permeability to support the flux needed to carry the power. This limits them to a material like Fair-Rite #61 or #67.*** And yet another negative for voltage baluns – any loss component in the ferrite core reduces the quality of the balance that the balun is providing, and real ferrites have losses. ***The result is that voltage baluns don't do a very good job of providing balance either!***

When used in a transformer (voltage) balun, or in a choke wound with parallel wire line, a core with high losses (#31, #43, #73, #77, #78) will convert much of the transmitter power into heat. The result are 1) high losses (that is, several dB of the transmitter output is lost in the balun); 2) balun performance may degrade due to heating; 3) the balun may overheat; 4) the balun (or the line) may fail due to overheating (that is, the line may melt and either deform or short, the ferrite may crack).

Although voltage baluns are still sold and advocated in articles about ham building projects by authors who don't know any better, most authorities believe that they cause more problems than they solve, and should be avoided when there are other good options. This author strongly concurs. There is a far better way to transform impedances using ferrite cores. See *Impedance Transformation with Current Chokes* later in this chapter.

Lossy Toroidal Coaxial Chokes Winding multiple turns of a coaxial feedline through one or more lossy toroidal cores is simply another (and usually better) way to construct a W2DU balun. It is better because 1) ***it makes much more efficient use of the ferrite*** than a string of beads; and because 2) ***it is easy to achieve much higher choking impedances in a very practical form and at reasonable cost*** than with any other form of balun; and because 3) ***a high level of performance can be obtained over a wide frequency range with a single part***. Conceptually, lossy toroidal coaxial chokes are no different from W2DU's original design, they have all of the advantages of other current baluns, and they can provide much better performance over greater bandwidth.

Disadvantages of the Reisert Toroidal Balun Because the design uses a low loss (high Q) material, the choke has a very high impedance only in the narrow range of frequencies to which it is tuned – roughly one-half octave. Below that range it is inductive with very low loss, and above that range it is capacitive, with loss that increases with frequency. It takes a lot of turns around a lot of cores to achieve acceptable performance on the lower HF bands, and a given choke is likely to be a good performer on only one ham band. Significantly better performance over a much wider frequency range can be achieved with lossy toroids. This has major implications when the objective is reducing receive noise coupled from the transmission line to the antenna – the lossy toroid choke is capable of significantly more suppression and significantly greater bandwidth.

Advantages and Disadvantages of the Solenoid Balun The principle advantage of solenoid chokes is their simplicity. Losses and dissipation are inconsequential. Solenoid baluns (coiled up coax) must be relatively large if they are to provide even relatively moderately high choking impedance (typically 500 – 1,500 ohms), and are only practical on the upper HF bands.

Using Common Mode Chokes As Baluns Maxwell taught us to use a common mode choke at the feedpoint of an antenna to minimize interaction of the feedline with the antenna – that is, to decouple the feedline from the antenna. This choke ("current balun") works by inserting a high common mode impedance in series with the feedline, ideally as close to the feedpoint as possible. The obvious question is, how much impedance is enough? There are (at least) four criteria.

Dissipation The choking impedance must be high enough to reduce common mode current to the level such that the choke cannot overheat and damage the core or the coax.

Pattern Distortion We would like the choking impedance to be high enough so that feedline current does not distort the pattern of the antenna.

Noise Coupling The choking impedance should be high enough that any noise current that may be received on the feedline behaving as an antenna cannot flow onto the intentional antenna.

RFI Prevention The choking impedance should be high enough that the feedline does not radiate transmitter current near susceptible equipment in your home (or a neighbor's).

How Much is Enough? Traditionally, "choke baluns" have been built around the assumption that a choking impedance on the order of 500 Ω was enough. Maxwell considered 1,000 Ω sufficient to eliminate pattern distortion, and considered his bead balun design sufficient to handle maximum legal power, although others have debated that assertion. In a self-published applications note, Chuck Counselman, W1HIS, suggested that a choking impedance of 5,000 Ω as a more suitable target value to optimize noise suppression. My work and experience prove him correct.

The Dissipation Question is one of the most important, yet can be tricky to get a good handle on. For a simple common mode choke in a pure 50 ohm system, it's simple – worst case puts the full transmitter voltage across the choke under the condition of infinite imbalance, so the power is simply $E^2/R$. For a 1.5kW CW or SSB transmitter, the PEP voltage is 275 volts, but heat is produced by the average voltage, and the average voltage, even with heavy compression is at least 6dB less (one half, 138 volts). 275 volts (keydown) will burn 15 watts in a choke that is 5,000 ohms resistive, which is our design criteria. But once we start talking or sending CW, the average power drops by 6dB (one quarter) to less than 4 watts! Key-down modes like AM, FM, and RTTY will still burn 15 watts, but most transmitters and amplifiers must be de-rated by 2-3dB for key-down modes. If the duty cycle is 66% (continuous contest CQ'ing with few answers), we'd be hitting the choke with about 10 watts key-down and 2.5 watts for CW and SSB.

The analysis above is for a 50 ohm system. What if the choke is on the output side of an antenna tuner (for example, up in the air at the feedpoint, or somewhere along the line) and the tuner is stepping up the impedance to match a higher impedance load? An impedance step-up of 4:1 doubles the voltage, which increases dissipation by 6dB, so our worst case CW or SSB dissipation is back to 10 watts. Increase the impedance to 400 ohms and CW/SSB dissipation rises to 14 watts. And all of this analysis is for an antenna that very badly unbalanced!

Can a choke that provides 5,000 ohms choking impedance dissipate this much power? First, virtually heating shows up primarily in the conductor(s), not in the core. Any choke wound according to our 5,000 ohm design criteria can handle 4 watts, even in an enclosure with no air circulation. 15 watts is no problem if the choke is exposed to air, and may work in an enclosure. 60 watts (keydown modes, full legal power) is likely to overheat a single core choke, but unlikely to cause problems with a big multi-core choke. It all depends on the choke we use. As we'll learn later on, we'll need 5 turns of RG8 through five 2.4" o.d. #31 toroids to achieve 5,000 ohms $R_S$ on 160, 80 meters, and 40 meters. We'll also learn about some bifilar chokes that can get us there.

Seven turns of RG8 will easily fit without a connector, four turns with a connector, so these are very practical chokes! Temperature rise is further minimized by leaving cores exposed to air flow (Fig 36 and 37). And remember, this is an extreme worst case set of operating conditions! [All cores look alike – the orange tape on these cores tells me these are mix #31.]

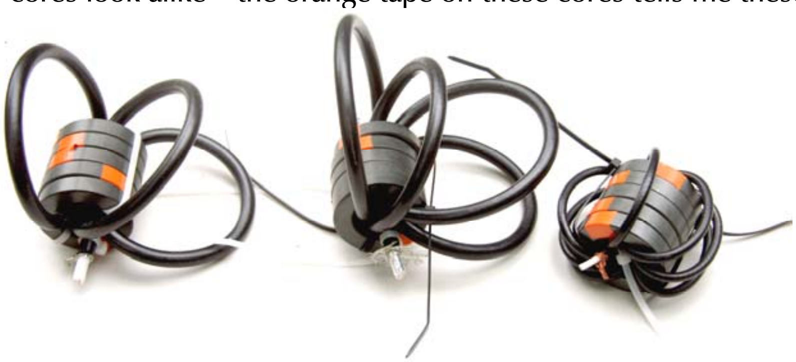

Fig 36 – Coaxial Chokes Wound to Minimize L and C

Fig 37 – A Bifilar Choke

How Chokes Fail *Common mode chokes subjected to high power fail when they are under-designed (that is, they have insufficient choking resistance),* and when they are mistreated (that is, when they are in line with an antenna that is badly unbalanced and run at high power levels). Using the analysis of Fig 36, it is easy to see how a choke that provides only 500 ohms choking impedance might easily overheat in this worst case condition.

Weight: A 2.4" o.d. #31 toroid weighs about 4 oz, and we need less than 8 ft of coax for five turns, so a five core choke on RG8 will add just about 4 lb to the weight of the antenna. The "Big Clamp-On" in Fig 5, data in Fig 39, can also be used for coaxial chokes; it weighs 11 oz, and is equivalent to three or four toroids. Can we use smaller coax? Probably, especially if our antennas are always reasonably well behaved. The failures mostly come when they are not. W8JI reports that he often feeds high dipoles for 160 and 80 with RG6 to reduce weight, thus reducing sag and the strain on support lines, and that a good RG6 will handle full legal power. My "workhorse" 160/80/40 dipole, fed with 150 ft of RG59B that I bought from "The Wireman" several years ago, worked fine with the full output of my Titan amp, even with a mismatch on the line that approached 2.5:1 during SSB contests. I've since replaced it with RG11 to reduce loss.

Choking Impedance and Noise Suppression Once we've satisfied the dissipation criteria, the ability of the common mode choke to suppress noise comes into play. The mechanism is simple. Any RF noise around your antenna will induce RF current on your feedline (and onto your antenna). When current flows on your antenna, you hear it in the receiver. The choke suppresses noise by adding a high resistance to common mode current between the feedline and your antenna, which in turn prevents it from showing up at the feedpoint and being sent back down the line to your receiver. For good noise suppression, the series choking impedance should be as high as possible. Again, 5,000 ohms is a good target value, and more could be better.

How Much Noise Reduction? Noise coupled from the feedline to the antenna will be reduced by 20 log $(I_2/I_1)$dB, where $I_2$ and $I_1$ are the common mode noise current with and without the choke. Once you've added enough choking impedance that the common mode current is dominated by that impedance, the noise reduction is 20 log $(Z_1/Z_2)$dB, where $Z_2$ and $Z_1$ are the common mode impedance with and without the choke. In other words, you get 6 dB of noise reduction for each halving of the current or doubling of the series impedance. This simple math explains why a 5K ohm choke is better than a 1K ohm choke!

Choking Impedance and RFI Prevention Again, a higher value of choking impedance is better. If the choking impedance is high enough to satisfy dissipation requirements, it's likely to be enough to prevent RFI in your home.

When should you use a "string of beads" choke, and when is a toroid choke better? The answer lies in factors like size, cost, and weight needed to achieve sufficient choking resistance. Both will work quite well – if enough core material and turns are used to provide enough choking impedance. ***A multi-turn choke on the right toroid is a far more efficient use of ferrite material, because impedance is multiplied by the square of the turns ratio,*** so a multi-turn toroidal choke is the clear winner below 30MHz. (See Table One in Chapter 7 for a cost and weight vs. benefits analysis.)

When are "string of beads" chokes OK? Many rules are made to be broken. A few years ago, K3LR asked me if it was OK to form a W0IYH string of beads using clamp-ons on his 10M antennas, where the feedlines had been carefully phased for stacking, and modifying their length to add multi-turn chokes wasn't practical. Fig 35 shows that the answer is yes – if enough beads are used to provide sufficient resistance that even if the feedline resonates with their inductance, the resistance still kills the common mode current. Fig 35 also shows that a relatively small "string of beads" can be quite effective on 6M and 2M. Fig 35 is computed for beads that are 0.562 inches long. Roughly half that number of 1.125-inch beads will provide equivalent performance.

Temperature Characteristics At HF, especially below 25 MHz, the #31 material is a bit less subject to thermal runaway than #43 and #73 materials. (See Fig 25 and the associated discussion.)

Impedance Transformation with Current Chokes Very good impedance transformation can be achieved by wiring good common mode chokes in series-parallel configurations. Examples are the high power "baluns" sold by DX Engineering to match 200 ohm, 300 ohm, and 450 ohm line to 50 ohm coax. The chokes are wired in parallel on the low impedance side and in series on the high impedance side. Fig 38 shows a 4:1 version of this design. The primary design considerations are that 1) the common mode impedance of each choke must be large enough that they do not short each other out or dissipate significant power; and 2) the common mode impedances of the chokes must reasonably matched each other. Two such chokes in series/parallel provides a 4:1 impedance transformation, three chokes provides a 9:1 transformation. The high power baluns manufactured by DX Engineering are Guanella "current" baluns.


Fig 38 – Current Choke (Guanella) Transformer

You can easily wind your own for a fraction of the cost following my guidelines for coaxial chokes on #31 or #43 cores, or with bifilar windings on those cores using the measured data in Appendix One as a guide. Putting them in an box, however, is not so easy. There will be stray capacitance between the chokes, and between the chokes and a conductive enclosure. With a non-conductive enclosure, there can be capacitance to metal around the enclosure. This capacitance adds to what is already there, so it can detune the chokes, lowering their resonant frequencies, and it can degrade system balance. In other words, building 1:4 and 1:9 chokes isn't as easy as it looks.

Dissipation W8JI, designer of the DX Engineering baluns, notes that connecting either terminal (or even a center tap) of the high impedance side to ground can cause the entire transmitter voltage to appear across one of the chokes. Tom's analysis is solid to the extent that it describes "worst case" conditions, but it misses the fact that the so-called "grounds" are usually thousands of ohms apart. It also assumes key-down conditions. But he is entirely correct that if you're going to ground one high impedance terminal of a 4:1 or 9:1 choke balun at the balun, you'll need a very high value of choking impedance to avoid dissipation problems when transmitting key-down modes at 1.5kW.

The same dissipation analysis we used for the simple common mode choke (page 28) applies to a choke that is part of a 1:4 current balun used according to its design criteria – connecting a 50 ohm source and a 200 ohm load, and with neither conductor of the 200 ohm side grounded. Sevick analyzes this choke with no ground on the 200 ohm side, and assumes half of the output voltage is across each choke. W8JI assumes a zero-impedance grounded center-tap, which places the full transmitter voltage across one choke, but no voltage across the other. The real world is somewhere between these two simplistic analyses, and every system will be different. What if the choke is used at the output of an antenna tuner that steps up the impedance to match 400 ohms? That worst case math increases the voltage by 3dB, which increases the dissipation in the choke by 3dB, so we have 7.5 watts in the choke for CW or SSB, 30 watts for AM, RTTY, or FM. In a 9:1

choke, worst case dissipation in any one choke can be 3-6dB greater (that is, double or 4 times).

In W8JI's worst case analysis of a 1:4 choke with one secondary terminal having a zero impedance short to the primary, he shows that one choke can have the full transmitter voltage while the other has either double the transmitter voltage or zero volts across it. Sevick's analysis places the transmitter voltage across each choke. Thus, in an unventilated enclosure, the worst case dissipation in the box is for 2X the transmitted voltage in one choke.

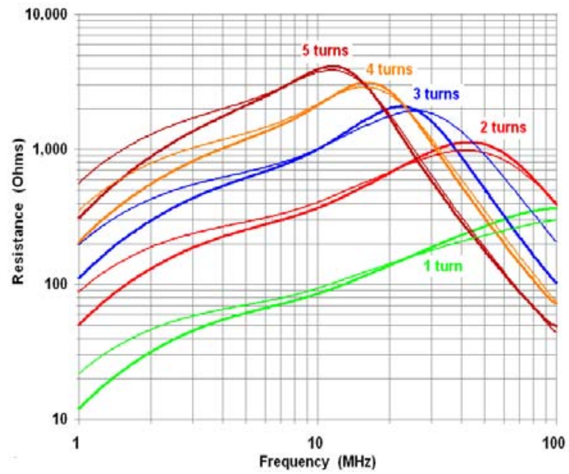


Fig 39 – The "Biggest #31 Clamp-On" (Fair-Rite 0431177081)

**The Biggest Clamp-On** Fig 39 is data for coils wound through the "biggest Fair-Rite #31 clamp-on" in Fig 5. Measured data for 1-5 turns through this part and a somewhat smaller one are shown in Fig 39. The heavier lines are the biggest clamp-on (1" i.d.); the lighter lines are for a 0.75" i.d. part. While the smaller part provides a bit higher impedance at low frequencies, it is far less useful because it doesn't allow as many turns of most cables on which we would like to use it. This big clamp-on is quite useful in many applications where it isn't practical to remove a large connector. Although we only measured small wire chokes up to five turns with this part, it can certainly be used with more than 5 turns of some cables. More turns moves the resonance even further down in frequency; it also increases the equivalent series resistance below resonance, -and for up to about one-half octave above resonance. See Fig 45 for coaxial chokes using the "biggest clamp-on."

**Chokes Wound with Coax** Up to this point, all of our measured data has been for small diameter wire wound around the core. The stray capacitance is a combination of the capacitance between the turns and the dielectric (the ferrite core) and the capacitance between the turns. The coaxial chokes of Fig 36 will have more stray capacitance than these smaller chokes or a bifilar choke like Fig 37), and they will have more inductance (by virtue of their greater length), but the loss component, mostly contributed by the ferrite, will be about the same as for the smaller chokes.

Fig 40a – Measuring Coaxial Chokes

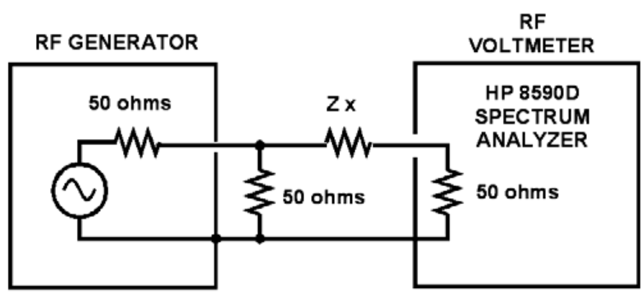


Fig 40b – Equivalent circuit

Fig 40a shows the test setup, and Fig 40b shows the equivalent circuit. Since the HP generator is designed to work into a 50 ohm termination and calibrated for that load, a 50 ohm "through" termination was added at the output of the generator. Without this termination, the generator voltage would be about 6 dB greater. (and the electronic attenuator might not work as well). The unknown impedance can then be computed from the voltage divider equation. For all values of unknown Z greater than 500 Ω, the error is less than 10%, and less than 5% for unknowns greater than 1,000 Ω. I measured the stray capacitance of this fixture as 0.4 pF at the terminals connected to the unknown impedance.

This is a very useful measurement setup, and can achieve reasonable accuracy for rather high values of impedance. K6MHE sent me a 13-turn choke he had wound on three #61 cores. I was able to measure an impedance greater than 150K ohms at resonance (15.5 MHz). The spectrum analyzer could be replaced by an RF voltmeter or scope, in parallel with a suitable load resistor.

How Much Stray Capacitance Is There? This is important, because it moves the resonance, and thus the frequency range over which the choke is effective, down quite a lot. To answer this question, I wound a lot of coax chokes (in the winding style of Fig 36) and measured them. Accurately measuring impedances in the range of 1K – 10K at HF is not easy, especially with Network Analyzers and Antenna Analyzers that make reflection-based measurements. Because the unknown impedances being measured are so far from the center of Smith Chart, very small values of stray reactance cause very large measurement errors. It is far more accurate to measure the unknown impedance (the choke) as the series arm of a voltage divider. I don't have access to a suitable Vector Network Analyzer (VNA), but I do own an HP 8657A RF generator and an HP 8590D Spectrum Analyzer. The 8590D includes a calibrated voltmeter that reads the voltage across a calibrated 50 ohm termination. Doing some math gives me the magnitude of the impedance. And since we already know that the choke is essentially a parallel resonant circuit, we can learn most of what we need to know about it by studying its Q and the values of Z far above and below resonance.

More Measurements: Fig 41 displays data obtained in this manner for RG8 chokes wound on stacks of #31 3.4" o.d. cores, in the style of Fig 36. Note that the resonant frequency falls both with more turns and with more cores in the stack. This is to be expected – in addition to the resistive impedance we are looking for, each core also adds inductance and capacitance, both of which lower the resonant frequency. Our goal is 5K ohms over a broad frequency range (at least three ham bands). Fig 40 shows very good options for 1.8-14 MHz, but makes it clear that it isn't easy to get more than about 3K at 30 MHz in a single choke, and it will be difficult to wind a single choke that covers 14-30 MHz (for use on a multiband antenna). Note that the "burbles" around 20 MHz are measurement errors resulting from artifacts of the active attenuator in my HP 8657A, and not characteristic of the actual choke.

Curve Fitting to Find R, L, and C values: Fig 42 is the impedance of a simple parallel resonant circuit consisting of a 320 $\mu$H inductance, a 4 pF capacitance, and a 6,600 ohm resistance. Fig 42 is simply a plot (using Quattro Pro) of the equation for the impedance of a parallel resonant circuit consisting of those component values. The values were selected so that the curve closely approximates the 5 turn choke wound on 7 cores in the vicinity of resonance – the red curve in Fig 41. This circuit has a Q of 0..73 at resonance. Note that as we move away from resonance by more than about 2 octaves (a 4:1 frequency change), the calculated curve increasingly deviates from the measured data. This should come as no surprise, since the permeability and the permittivity of the ferrite material vary with frequency.

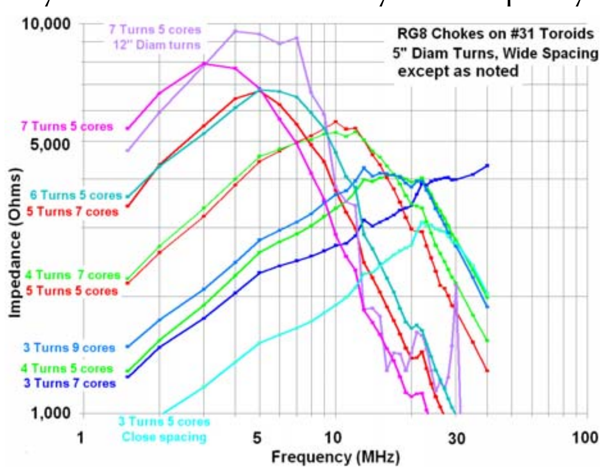


Fig 41 – Measured Impedance of RG8 Chokes wound on stacks of #31 2.4" toroids

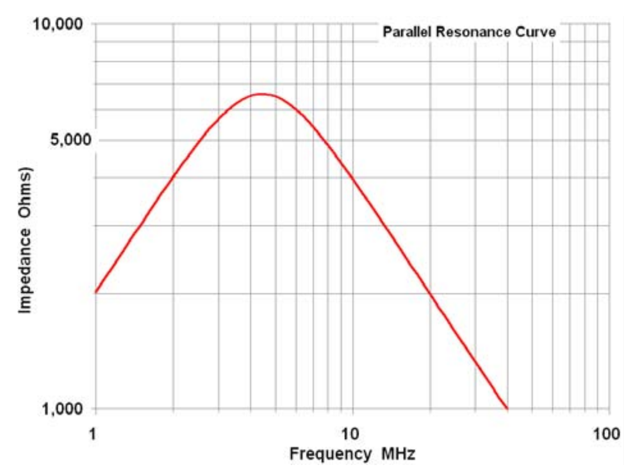


Fig 42 – Impedance of a parallel resonant circuit of 320 uh, 4 pF, and 6,600 ohms

Note that for this particular choke, 4 pF is the total parallel capacitance around 4.5 MHz – the capacitance between the coax and the ferrite, plus the capacitance between the turns of the coax that is close together within the cores, plus the capacitance between the turns of the coax that are widely spaced outside the ferrite cores, plus the 0.4 pF capacitance of our test fixture. How about the capacitance at 30 MHz? If we assume that the inductive reactance has dropped by a factor of about 8 and the capacitive reactance has increased by the same ratio, the capacitance at 30 MHz is approximately equal to $1/(2\pi f Z)$, or about 5.3 pF.

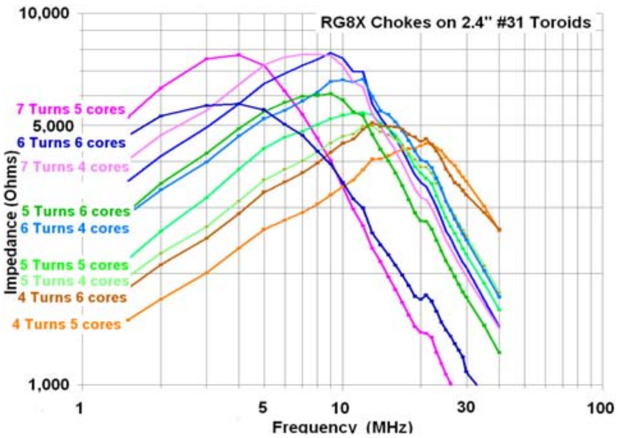


Fig 43 – Measured Impedance of RG8X Chokes wound on stacks of #31 2.4" toroids

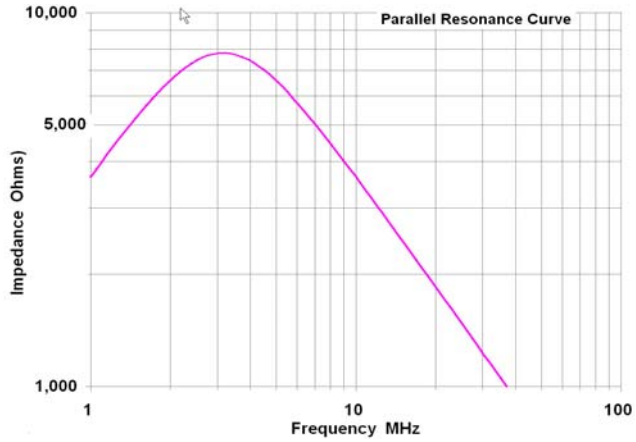


Fig 44 – Impedance of a parallel resonant circuit of 590 uh, 4.3 pF, and 7,800 ohms

Fig 43 shows data for chokes wound using RG8X, and Fig 44 is a simple parallel resonant circuit that approximates a 7 turn choke wound around 5 cores (the magenta curve in Fig 42). The capacitance value is a bit higher, and the Q is a bit lower. Applying the same techniques to the 4-turn 5-core RG8X choke of Fig 43 (the orange curve) yields circuit values of 56 uh, 1.3pF, 4,400 ohms, and a Q of 0.67.

How good are these circuit values? Certainly they are a first approximation, based on an approximate equivalent circuit. I would trust them to about 25% – there easily might be enough stray L and C in the test setup to contribute that much error. And remember, L, R, and C contributed by the ferrites all vary because the complex permeability and the permittivity of the ferrites vary with frequency. So the answer to our question, "How much capacitance is there?" is, "typically between about 1 pF for a small choke and about 7 pF for a larger one with a lot of turns." The other part of the answer is, we can control that capacitance and keep it small enough that our chokes work by paying reasonable attention to winding style.

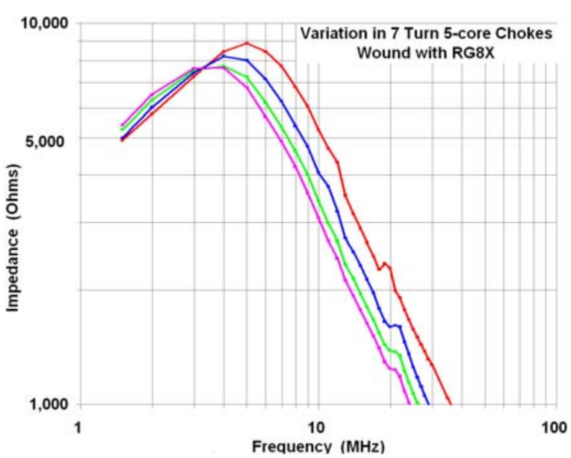


Fig 45 – Variation of chokes with winding style, coax outer jacket material

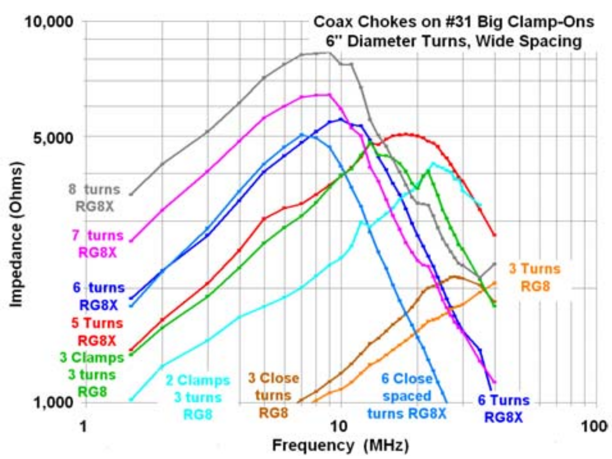


Fig 46 – Measured Impedance of Chokes wound on the "Big #31 Clamp-on"

<u>Your Mileage Will Vary</u> Fig 45 shows the variation in impedance that can occur based on the details of how the choke is wound, and on the jacket material. The magenta curve is for a choke

whose turns are tightly bunched together both inside and outside the toroids. Both the stray capacitance and the inductance of the coax are maximized (for a given number of turns and winding diameter). The other three curves are for chokes whose turns are intentionally spread wide apart outside the toroids. One of them uses somewhat larger diameter turns and a different type of RG8X. Capacitance is a function of spacing, geometry, and the dielectric material. The diameter of the shield, as well as the thickness and permittivity of the jacket material all can cause variations in the capacitance. In all of the measurements, I saw the greatest unintentional variation from one to another with chokes having a lot of turns of RG8X, and the least with those wound using RG8.

Tolerances in the Ferrites Fair-Rite #31 cores are considered suppression components, and because in the world of suppression, more impedance is considered better, their performance specifications are typical minimum values of impedance over a range of frequency. That's fine for our purposes, but don't expect exact agreement from one part or batch to another.

Chokes and Modeling A wire can be added to an NEC model for a dipole (or other antenna) to analyze the contribution of common mode current on the coax shield to antenna performance – simply connect a wire from one side of the feedpoint to ground. Beginning with version 4 of W7EL's excellent EZNEC+, we can add a network, including a parallel RLC network, to any of the wires in the model. Use the values of R, L, and C that are determined empirically (see Figs 41 and 43, and the associated discussion). We might also add a nearby feedline that we suspect might need an "egg insulator" choke, and study the results with and without the choke.

The Biggest Clamp-On Fig 46 is measured data for various coaxial chokes wound through the "biggest #31 clamp-on" of Fig 5 and Fig 39. This is a very useful and versatile part, because it can easily be applied to cables without removing a large connector, or without disconnecting them from an existing system.

Chokes in Series As we learned earlier, the impedances of multiple chokes in series will add, taking the reactances of each choke into account. That is, if one choke looks inductive and resistive at a given frequency and the other choke looks resistive and capacitive, the resistances will add, but the capacitance and inductance will cancel (at least partially). Fig 47 is measured data for three combinations that are potentially useful for multiband antennas.

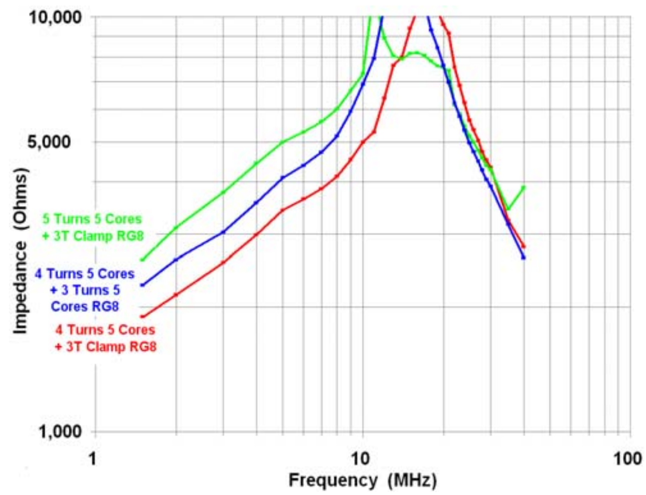


Fig 47 – Impedance of Chokes in Series

Bifilar Ferrite Chokes can be as effective as coaxial chokes in blocking common mode current, and a good small choke can handle 1.5kW. To prevent excessive dissipation in the choke, the bifilar winding must have very good symmetry and the 5,000 Ω impedance guideline must be observed.

Effect of Wire Insulation Fig 48 shows that the wire insulation shifts the resonant frequency. The increased overall diameter also reduces the maximum number of turns that can be wound on any given core. Sixteen turns appears to be the practical limit for #14 THHN without overlapping turns.

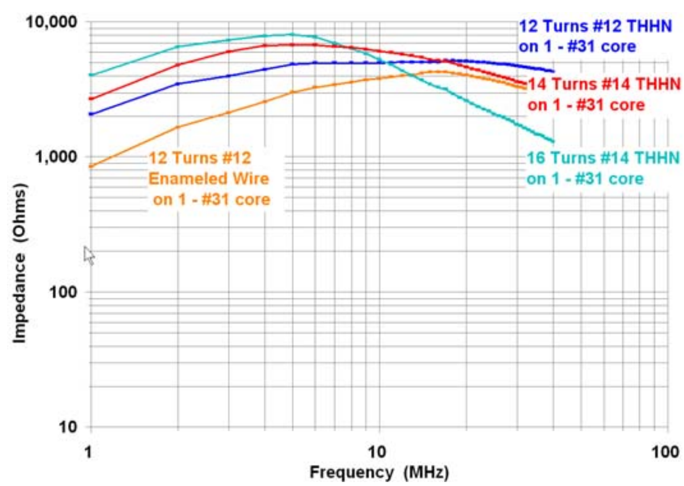


Fig 48 – Some Useful Bifilar Chokes

**Bifilar Chokes and Transmission Loss** A bifilar choke wound around a toroid forms a short transmission line whose impedance may be different from that of the line into which it is inserted. Thus, a bifilar choke can introduces some mismatch. A tightly spaced enameled #14 bifilar winding is very close to 50 ohms. Tightly spaced #14 THHN windings are close to 100 ohms. Not including mismatch, copper loss in a bifilar choke is quite small – for #14 wire, less than 0.01 dB at 3.5 MHz and 0.03dB at 28 MHz. Any additional loss due to mismatch is unlikely to exceed 0.2dB, and will be distributed over the entire length of the line.

**Coaxial Chokes and Transmission Loss** Coaxial chokes do not introduce any mismatch, so the loss of a coaxial choke is simply the loss for the additional length of coax required to wind it. At 2 ft/turn, chokes wound following Cookbook guidelines should add no more than about 0.05 dB loss if wound with low loss RG8; and no more than about 0.15 dB if wound with a low loss RG8X.

**A Common-Mode Choke as an "*Egg Insulator*"** Have you ever noticed the egg insulators in the guy wires for an AM broadcast tower? Their function is to prevent the guy wires from interacting with the antenna. The egg insulators break the guy lines into small enough pieces that each is a small fraction of a wavelength at the operating frequency. Often, one or more ***feedlines*** in a typical ham station may interact with another antenna. The result of this interaction is unpredictable at best; there's a good chance that the result will degrade antenna performance. Seasoned antenna engineers know that any near-resonant object within several wavelengths of an antenna can interact with it. We also know that most interaction is multiplied by the cosine of the angle between the wires. This means that interaction is likely to be greater for wires that run in parallel with each other, and far less likely if they are at 90 degrees to each other.

Here's an example from my own station. A few years ago, I installed a top-loaded vertical (with a good radial system) that was working quite well on 80 and 160 meters. A month or two later, I added a fan dipole for 20, 15, and 10 meters at about 100 ft. Most of the 150 ft-long feedline for the fan is vertical, rising about 90 ft from the vertical antenna, and it runs right past the vertical's feedpoint to get to the shack. I noticed that the vertical wasn't working at all on 80, and wasn't working nearly as well as it originally did on 160. On a hunch, I added a common mode choke at the transmitter end of the feedline for the fan dipole and the 80/160 vertical started working again!