Coaxial Transmitting Chokes

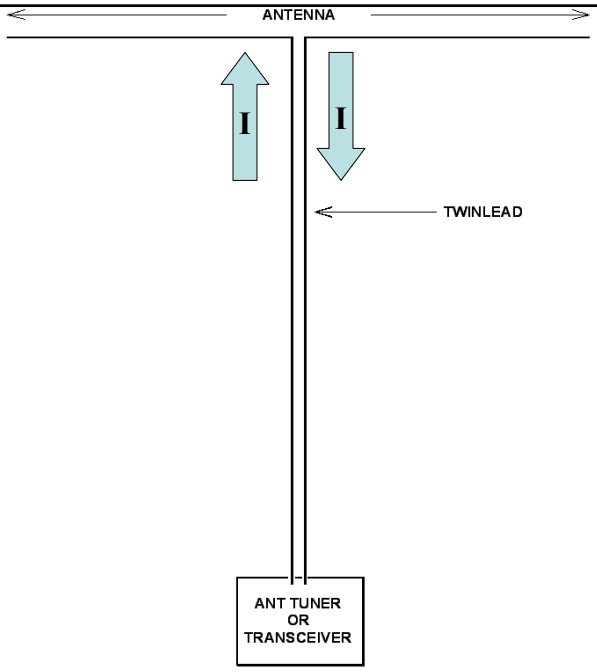
Jim Brown K9YC
Santa Cruz, CA

http://audiosystemsgroup.com

Understanding Common Mode and Differential Mode Currents on Transmission Lines

Differential Mode Current

- Transmission line carrying power from transmitter to antenna, or from antenna to receiver
- Signal is voltage <u>between</u> the two conductors
- Current flows out on one conductor and returns on the other

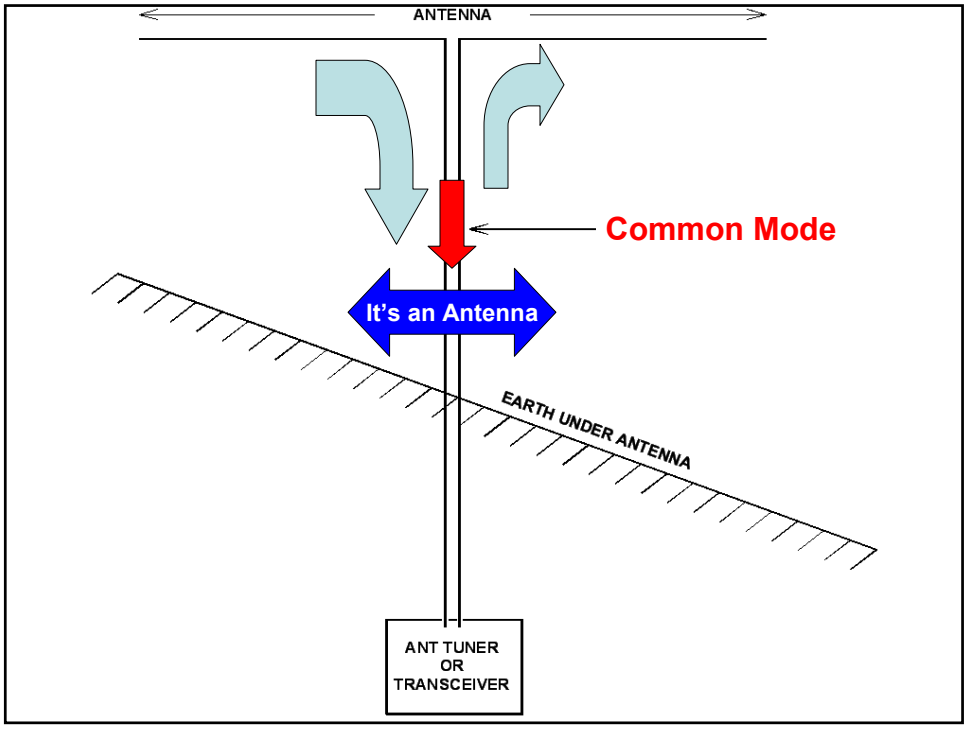


Differential Mode Current

- Transmission line carrying power from transmitter to antenna, or from antenna to receiver
- Signal is voltage between the two conductors
- Current flows out on one conductor and returns on the other
- Fields exist between the two conductors
- No radiation from ideal line
  - Field of outgoing conductor cancels field of return conductor

Common Mode Current

- Equal and flowing in the same direction on all conductors of balanced lines
- Current flows lengthwise on the line
  - No cancellation of one current by another, because they're in polarity
- Line acts as long wire antenna
  - It radiates and it receives



Ham Antennas and Balance

- **Most ham antennas are <u>unbalanced</u> by their <u>surroundings</u>, even when fed by a balanced source and line**

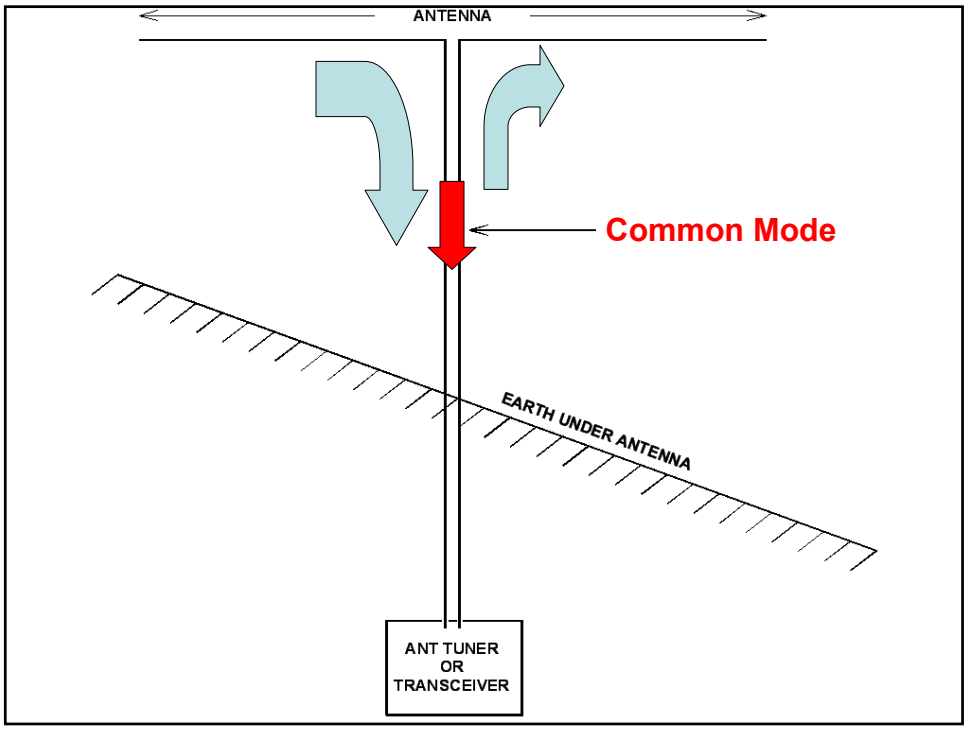
What Makes a Circuit Balanced?

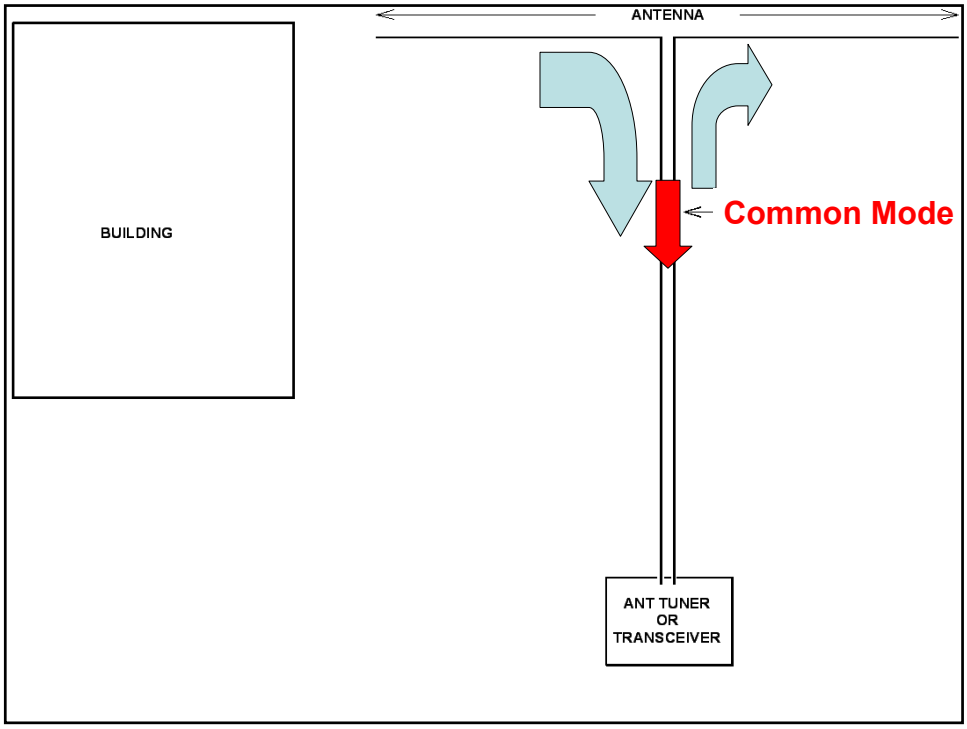
What Makes a Circuit Balanced?

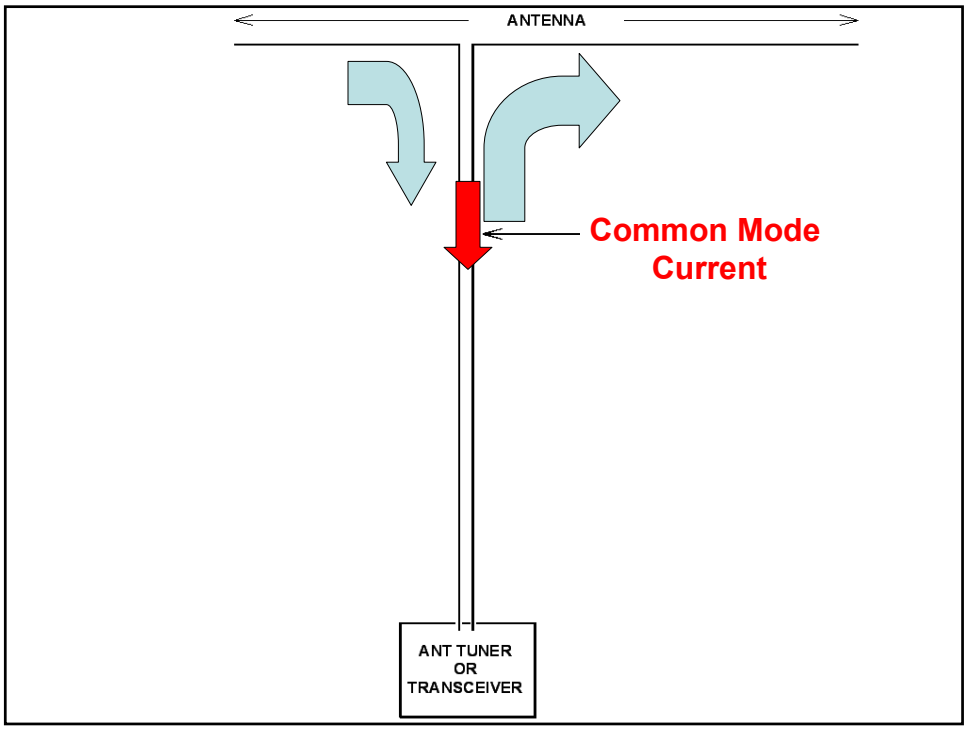
- The impedances of each conductor to the reference plane are equal
- Balance is not defined by voltage or current
- Imbalance impedances cause unbalanced currents

Ham Antennas and Balance

- **Most ham antennas are <u>unbalanced</u> by their <u>surroundings</u>, even when fed by a balanced source and line**
  - **Unequal capacitances to nearby conductors**
  - **Unequal inductive coupling to nearby conductors**
  - **Trees, buildings, towers, terrain**
  - **Feedline comes off at an angle**
  - **Coax is not a part of these imbalances**




ANTENNA
BUILDING
Common Mode
ANT TUNER
OR
TRANSCEIVER


ANTENNA
Common Mode
Current
ANT TUNER
OR
TRANSCEIVER

Unbalanced Antennas and Lines

- If the antenna is unbalanced
  - Unequal voltage and current to earth
  - Unequal currents on the feedline
  - The difference is common mode current, and it radiates from the line
- Coax did not cause the imbalance in these antennas!
- Coax simply adds to the imbalance

The Fields around Coax and Twinlead are Very Different

Coax is Special

- All the differential power (and field) is confined inside the coax
- All the common mode power (and field) is outside the coax
- A ferrite core surrounding coax sees only the common mode power (and field)

Coax is Special

- Skin effect splits the shield into two conductors
  - Inner skin carries differential mode current (the transmitter power)
  - Outer skin carries common mode current (the current due to imbalance)

Twinlead Has Leakage Flux from Differential Current

- This leakage flux is not confined to the region between the conductors, but instead spills to the area immediately surrounding the conductors
- Leakage flux causes very little radiation, but it will cause heating in a lossy medium!
  - Like a ferrite core

How Much Leakage Flux?

- Depends on mutual coupling between conductors
  - Depends on conductor-to-conductor spacing
  - How close together can conductors be?
- Coupling coefficient of 60-70% typical
  - 30-40% leakage flux in best balanced cables
  - 50% or more in ladder line

We'll talk more about all this later on

Now We Can Talk About Common Mode Chokes!

What's a Common Mode Choke?

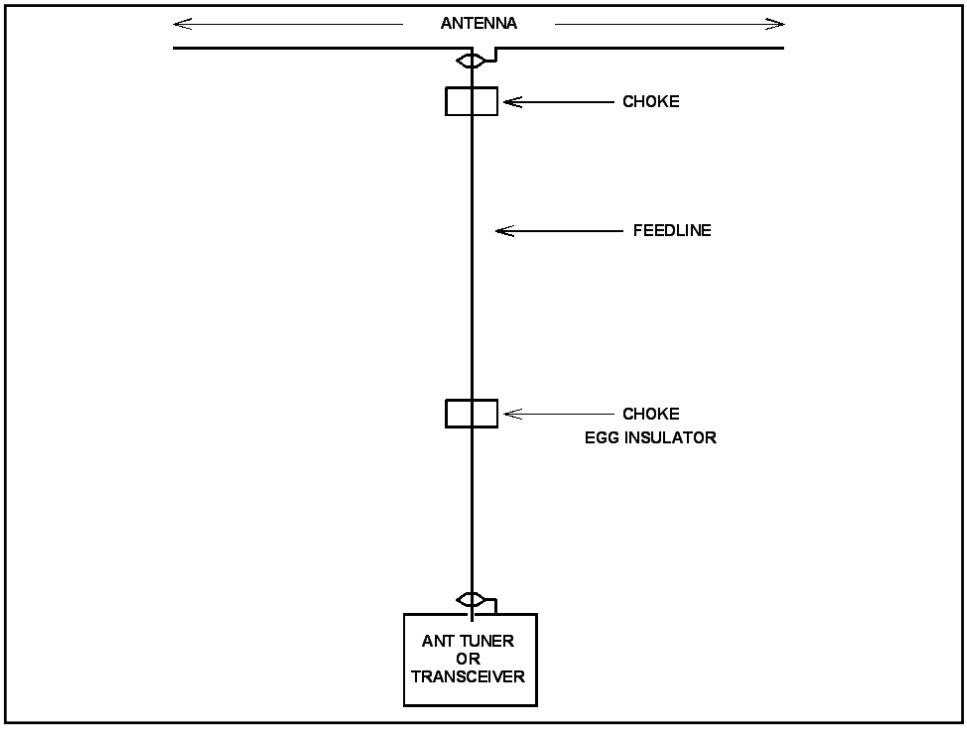
- A circuit element that reduces common mode current by adding a high impedance in series with the common mode circuit
  - Reduces radiation from the cable
  - Reduces reception by the cable

Some Common Mode Chokes

- A coil of coax at the antenna
- A string of ferrite beads around coax (Walt Maxwell, W2DU)
- Multiple turns of transmission line through a toroid (Joe Reisert, W1JR) or stack of toroids (W1HIS, K9YC)
- Most 1:1 “baluns” are common mode chokes

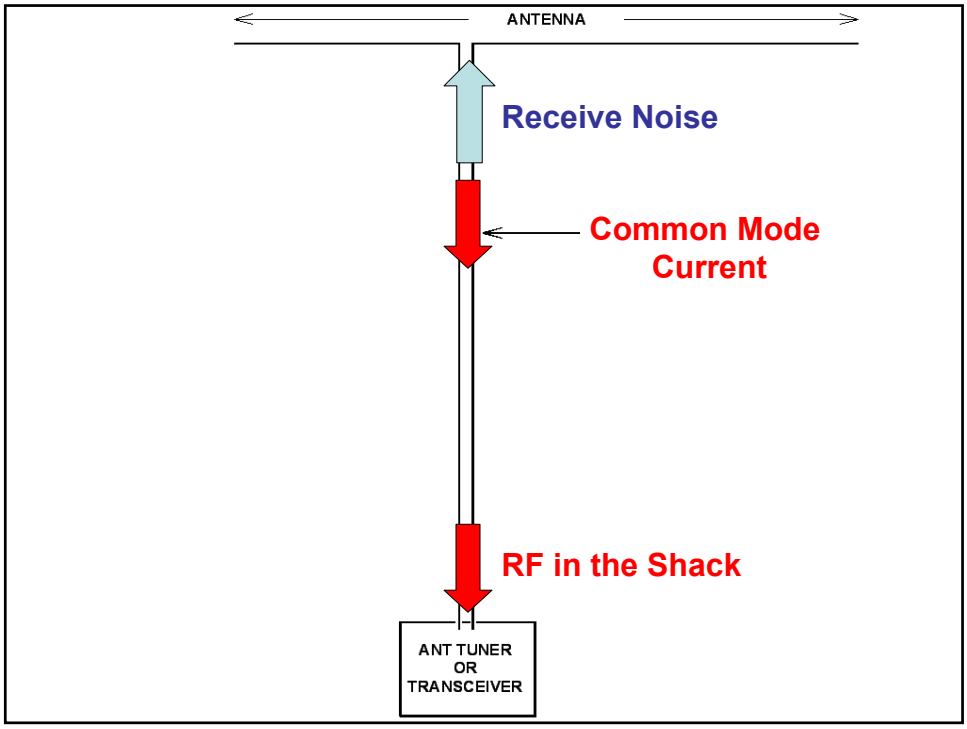
Some Common Mode Chokes

- Some 2:1, 3:1, and 4:1 “baluns” are also common mode chokes
  - But the few I’ve measured aren’t very good common mode chokes



Why Transmitting Chokes?

- Isolate antenna from its feedline
- Reduce receive noise
- Keep RF out of the shack
- Minimize antenna interaction
  - SO2R, Multi-multi
  - Dipole feedline and vertical antenna



Design of Transmitting Chokes

- Higher impedance is better!
  - Reduces common mode current
  - Reduces noise
  - Reduces interaction
  - Reduces RF in the shack
  - Reduces dissipation
- Resistance is better than reactance

Why is Resistance Better?

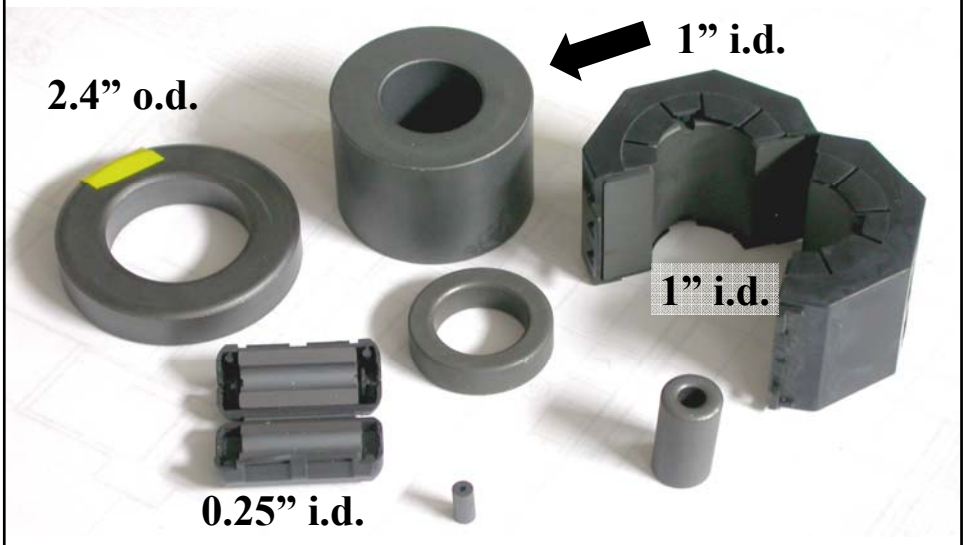
- We want to reduce the current
- A cable shorter than λ/4 is capacitive
  - Series inductance resonates with it and increases the current
- A cable longer than λ/4 (and shorter than 3λ/4) is inductive
  - Series capacitance resonates with it and increases the current
- Resistance always reduces current

Ferrite Chokes are the Answer!

What's a Ferrite?

- A ceramic consisting of an iron oxide
  - manganese-zinc – 1-30 MHz (AM broadcast, hams)
  - nickel-zinc – 30 MHz-1 GHz (FM, TV, cell phones)
- Has permeability (μ) much greater than air
  - Better path for magnetic flux than air
  - Multiplies inductance of a wire passed through it
- Is increasingly lossy at higher frequencies

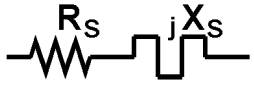
Different sizes and shapes



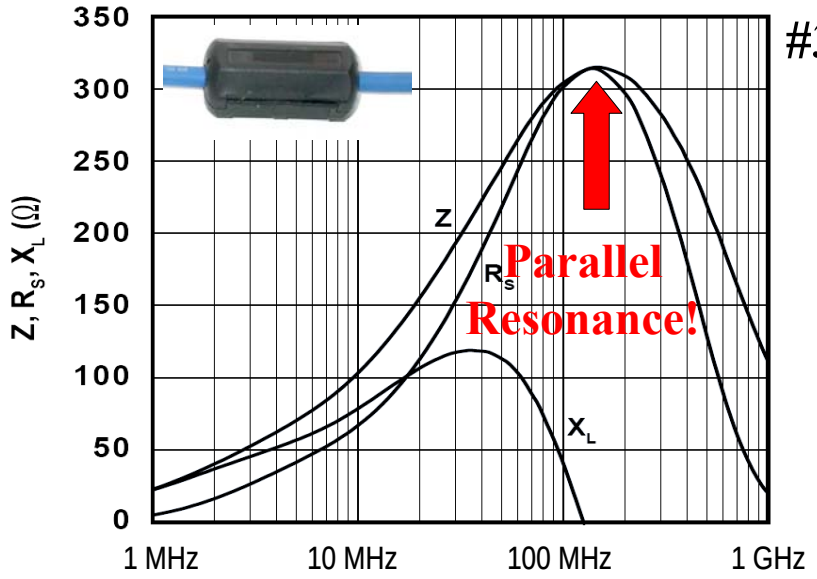
What's Different?

- The "***MIX***" − the chemical formula of the iron oxide!
- A ceramic consisting of an iron oxide
  - manganese-zinc (MnZn) – 1-30 MHz (AM broadcast, hams) #31, #77, #78
  - nickel-zinc (NiZn) – 30 MHz-1 GHz (FM, TV, cell phones) #43, #61, #67
- #31 is a new MnZn *mix* that behaves like #43 at HF and VHF, but is much better below 5 MHz

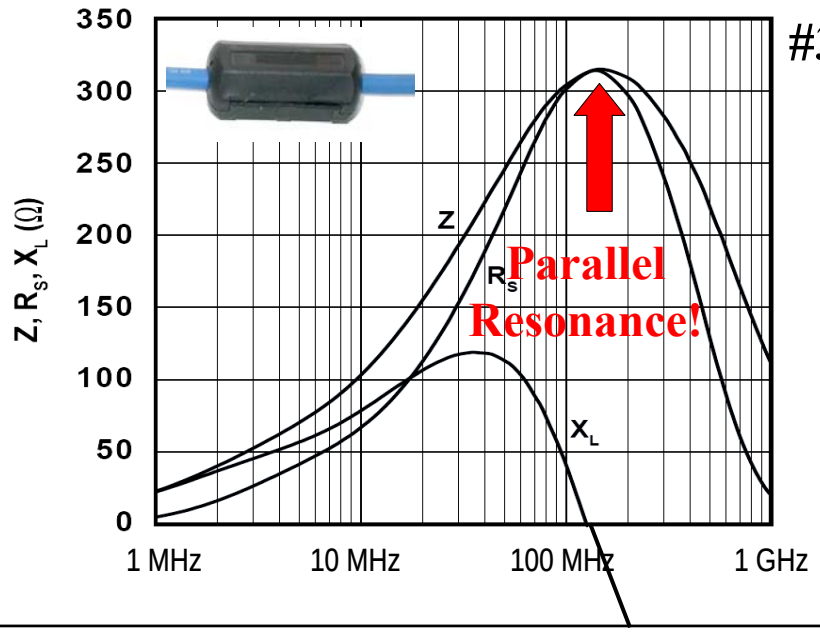
A simple equivalent circuit of a wire passing through a ferrite



R_S and X_S vary with frequency!

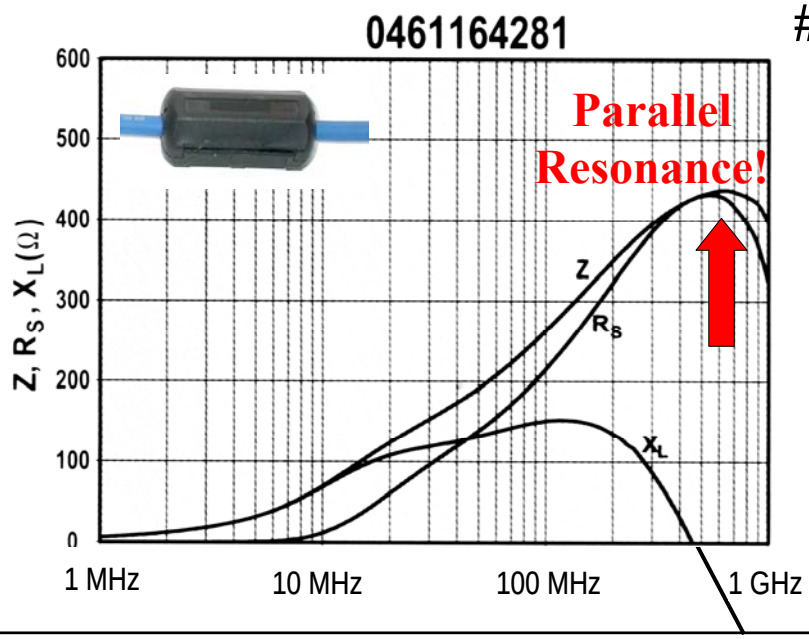


R_S and X_S vary with frequency!



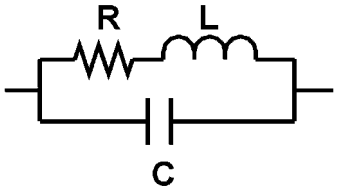
A Ferrite for UHF Suppression

#61

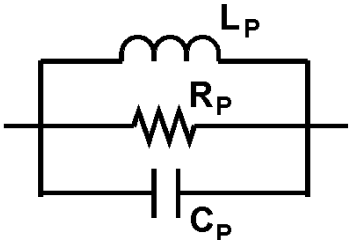


Equivalent Circuit of a Ferrite Choke

Low Frequencies

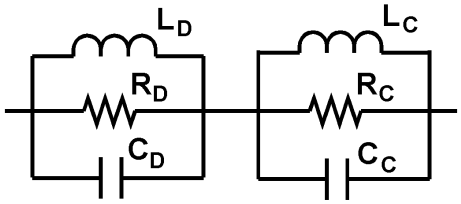


Mid-Frequencies



High Frequencies

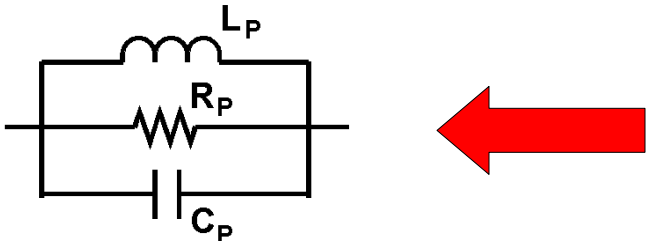
More General Equivalent Circuit



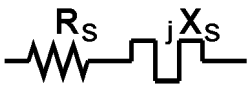
Including Dimensional Resonance

(more than we have time to talk about today)

We'll Use This Physical Equivalent Circuit to Understand the Choke



Data Sheets Use This Equivalent Circuit to Graph the Impedance



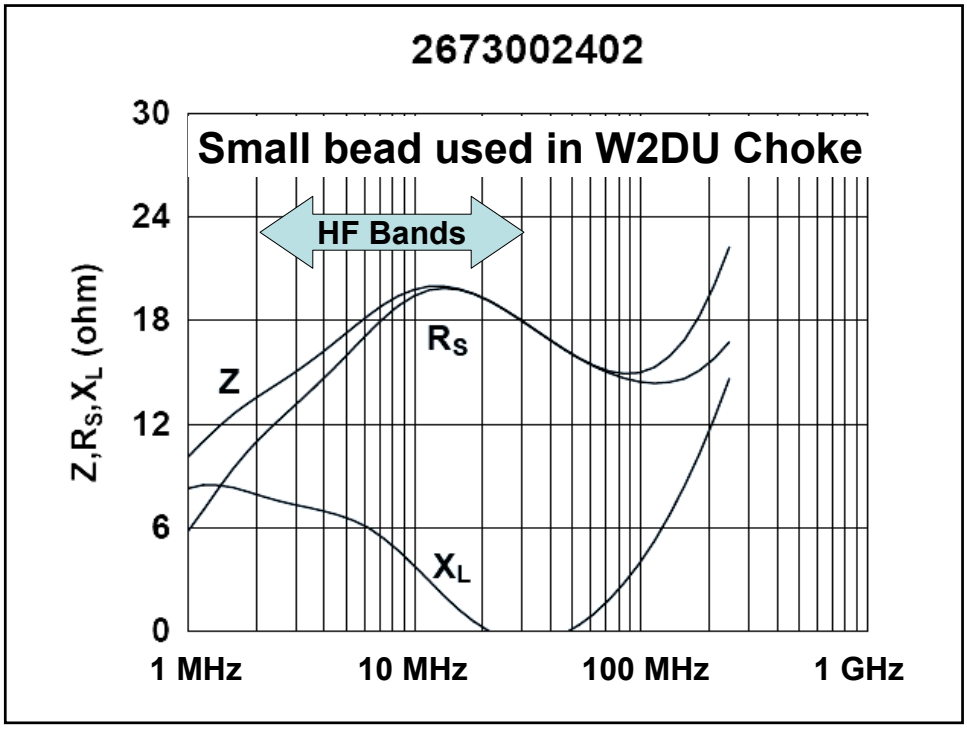
Where's the Capacitance here?

Where's the Capacitance here?

From the wire at one end of the choke to the wire at the other end, through the permittivity of the ferrite (it <u>is</u> a dielectric!)

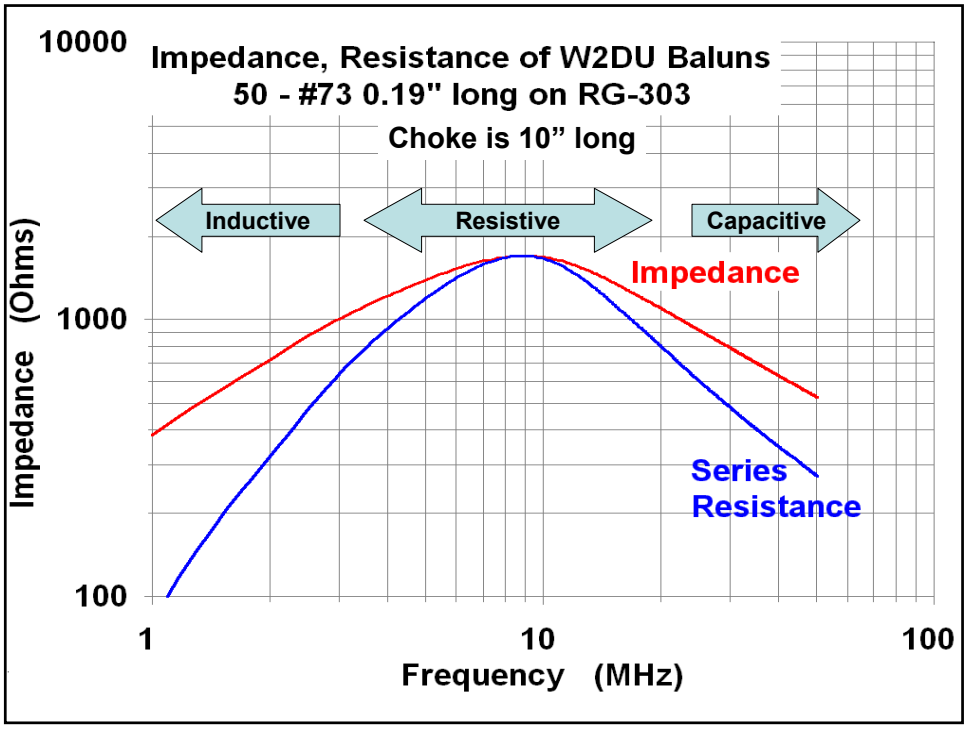
“Strings of Beads” (W2DU, W0IYH Baluns)

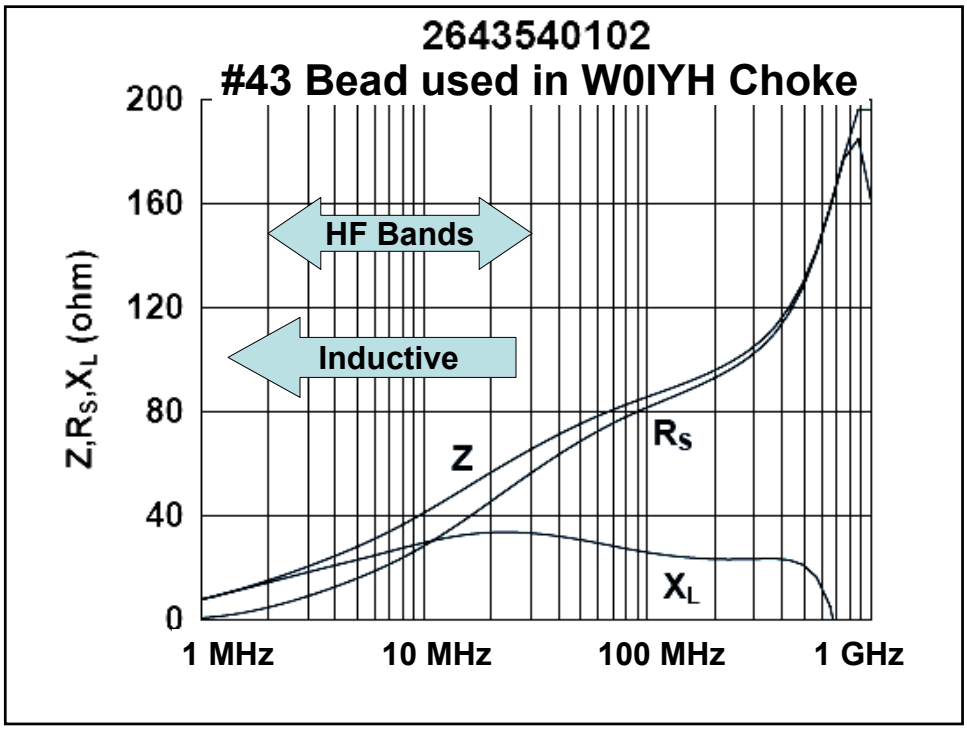
A String of Different Beads



W2DU Choke

- A "string of beads" choke
  - Impedances in series add
  - 50 beads = 50 x Z of one bead
- W2DU used #73 mix (a very good choice)
- Increasingly resistive above 3 MHz
  - Less sensitive to feedline length
- Much better than bead of WØIYH choke
- Many more beads are needed
  - They're small and cheap (good)
- #73 only made to fit RG58 or RG303


Impedance, Resistance of W2DU Baluns
50 - #73 0.19" long on RG-303
Choke is 10" long
Inductive
Resistive
Capacitive
Impedance
Series
Resistance
10000
1000
100
Impedance (Ohms)
1
10
100
Frequency (MHz)


2643540102
#43 Bead used in W0IYH Choke
HF Bands
Inductive
Z
Rs
XL
200
160
120
80
40
0
Z,Rs,XL (ohm)
1 MHz
10 MHz
100 MHz
1 GHz

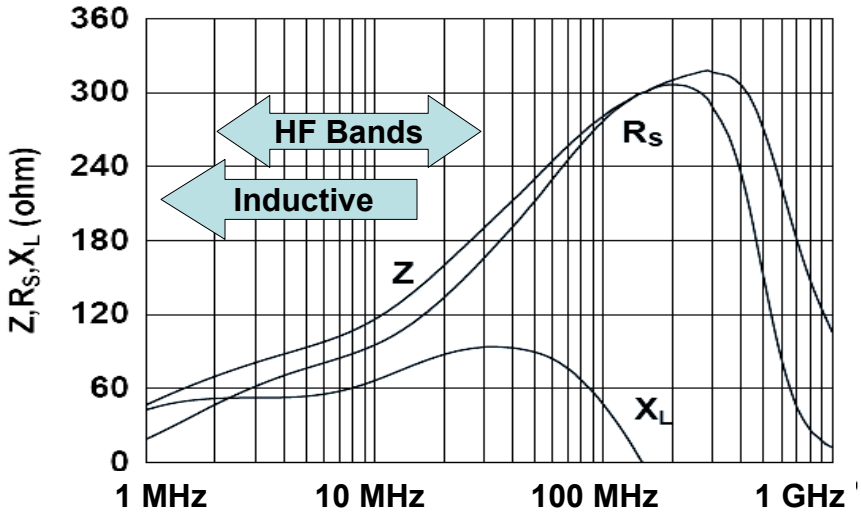
W0IYH Choke

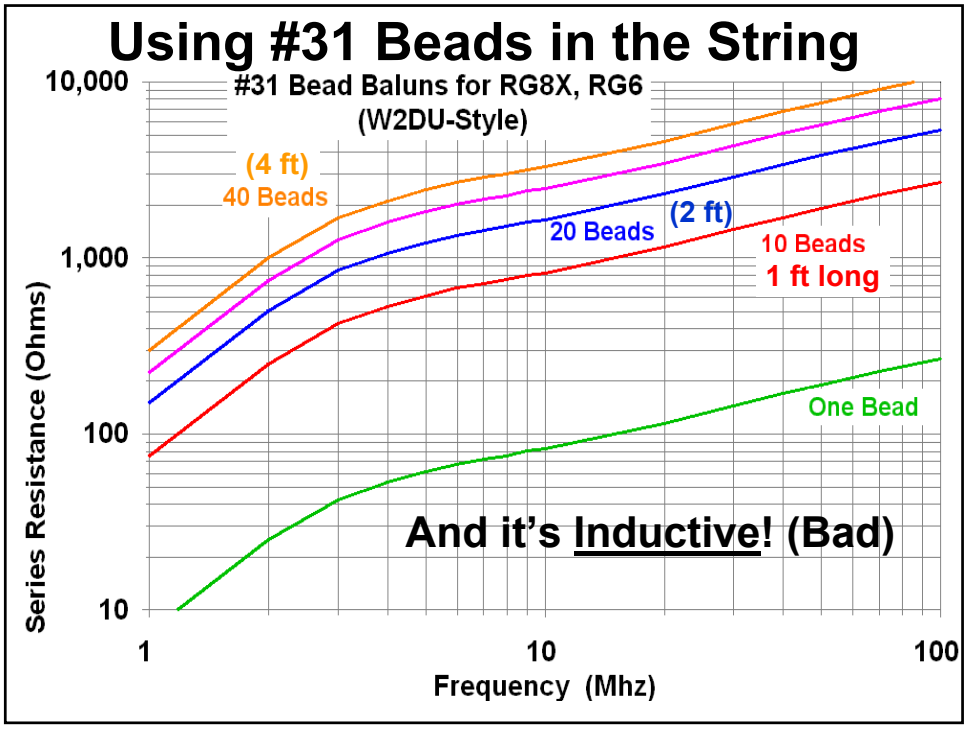
- Also a “string of beads” choke
- Predominantly <u>inductive</u> below 25 MHz
  - Very sensitive to feedline length
  - Inductance resonates with a capacitive line
- Increasingly resistive above 25 MHz
  - Much less sensitive to feedline length
- Not very effective below 15 meters!

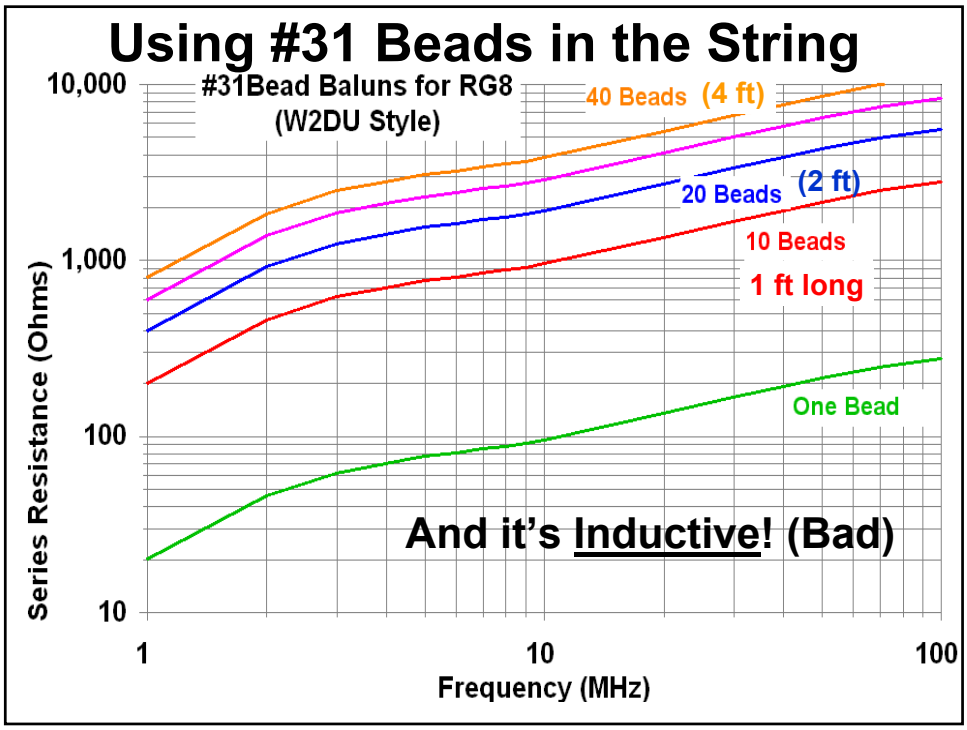
A #31 Bead for the String

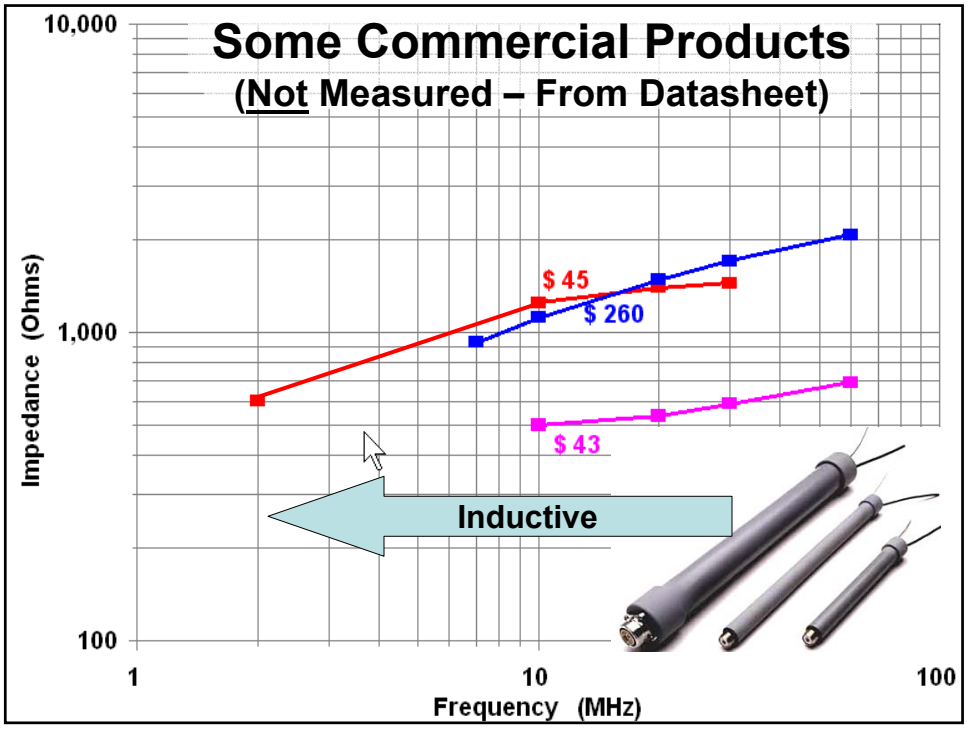
1” o.d. x 1.125” long (Fits RG8)

2631102002




Using #31 Beads in the String
#31 Bead Baluns for RG8X, RG6
(W2DU-Style)
(4 ft)
40 Beads
(2 ft)
20 Beads
10 Beads
1 ft long
One Bead
And it's Inductive! (Bad)
10,000
1,000
100
10
Series Resistance (Ohms)
1
10
100
Frequency (Mhz)

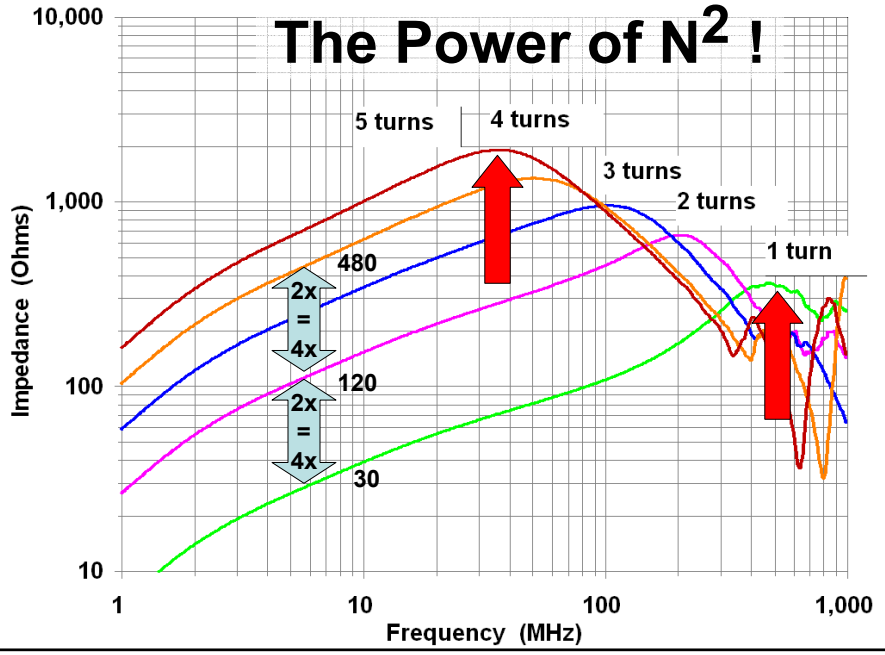

Using #31 Beads in the String
#31Bead Baluns for RG8
(W2DU Style)
40 Beads (4 ft)
20 Beads (2 ft)
10 Beads
1 ft long
One Bead
And it's Inductive! (Bad)
10,000
1,000
100
10
Series Resistance (Ohms)
1
10
100
Frequency (MHz)



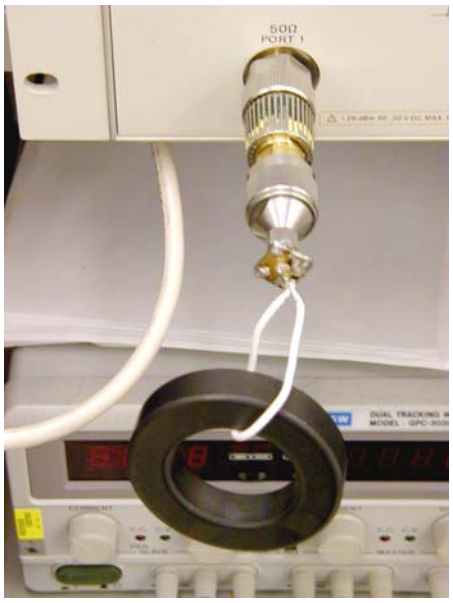
There's A Better Way to get Higher Impedance

- Inductance increases as N^2
- Inductively coupled resistance increases as N^2

Measured Data for #43 Toroid Chokes



HP8753C w/HP85046A S-parameter Test Set (by my anonymous collaborator)



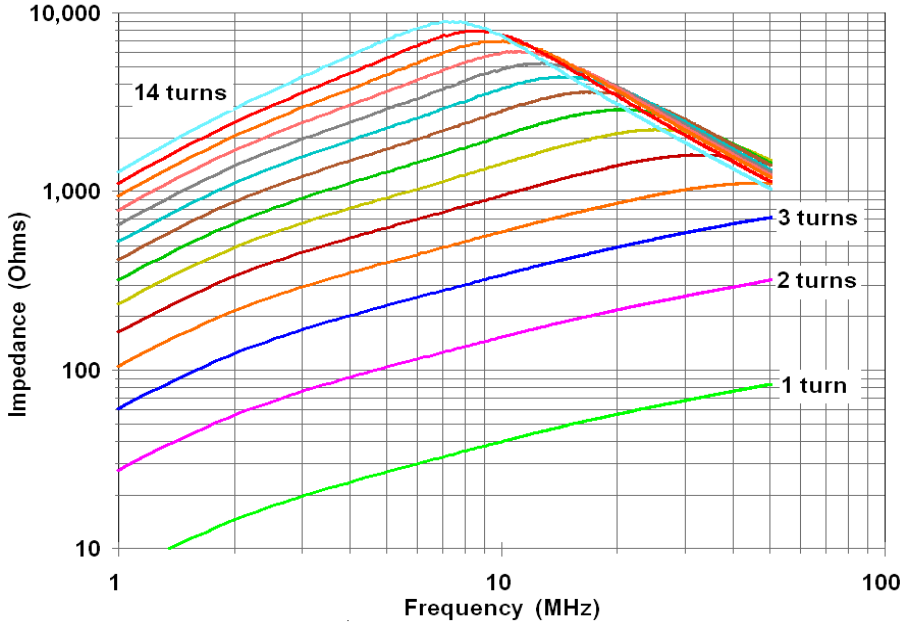
Why the Resonance Moves Down

- Inductance increases as N^2
- Inductively coupled resistance increases as N^2
- Capacitance increases with N
  - Capacitance between turns
  - Capacitance through the ferrite core
  - More capacitance with much bigger wire (like coax)

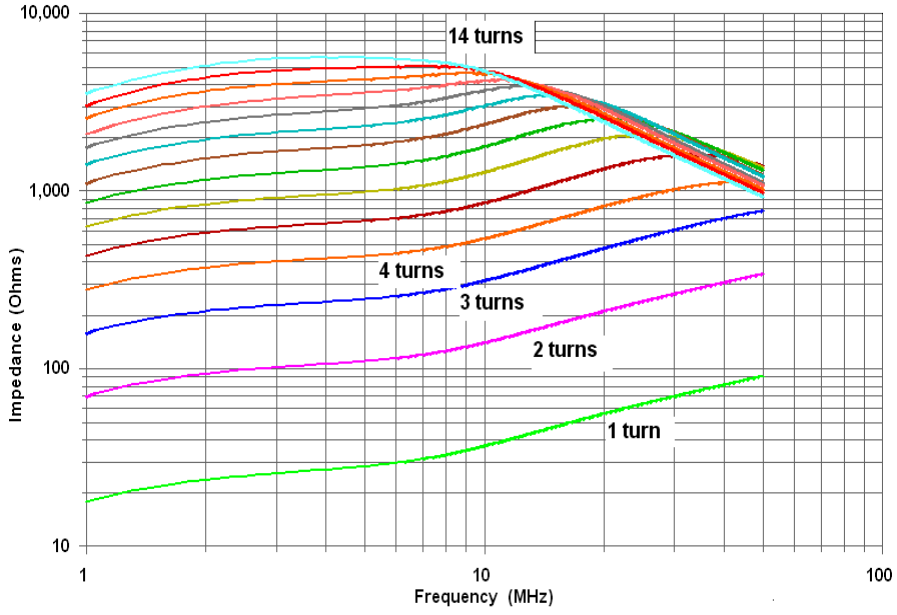
The Power of Turns at HF and MF

- Moves the resonance down from VHF to HF
  - More inductance
  - More capacitance
- Multiplies impedance at resonance
  - But not by N^2, because resonance has moved lower in frequency

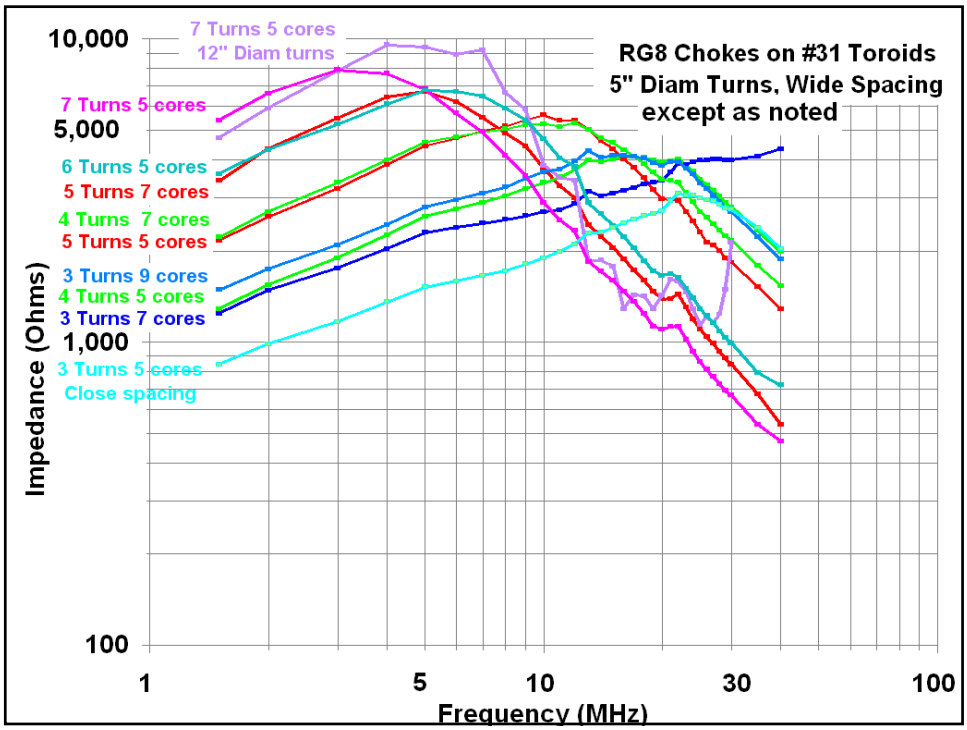
Measured Data for #43 Toroid Chokes

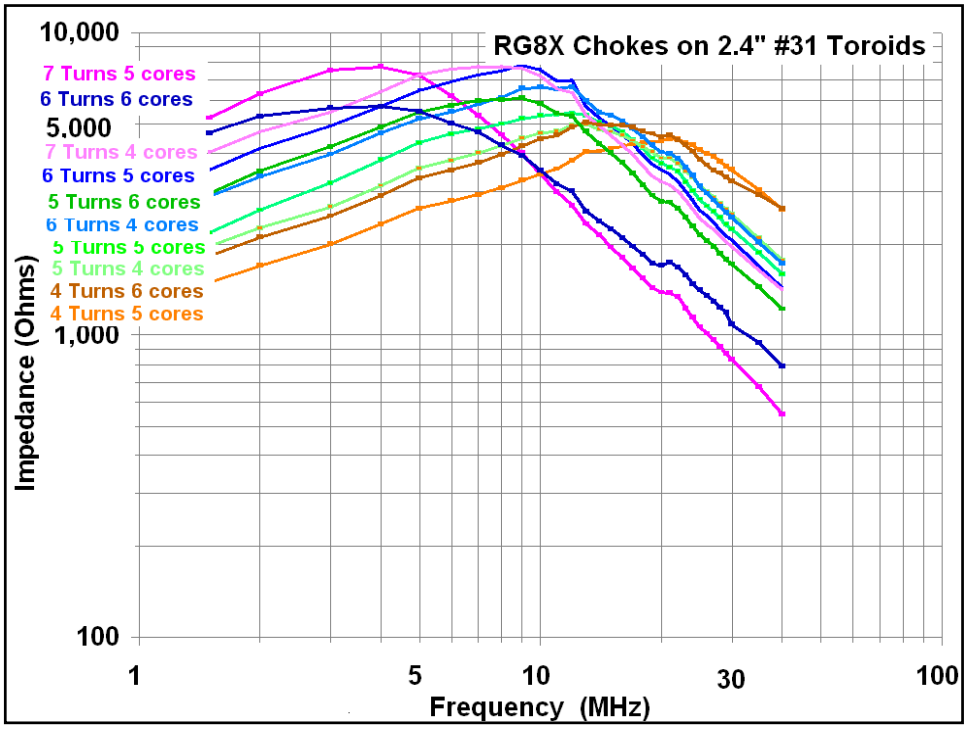


Measured Data for #31 Toroid Chokes

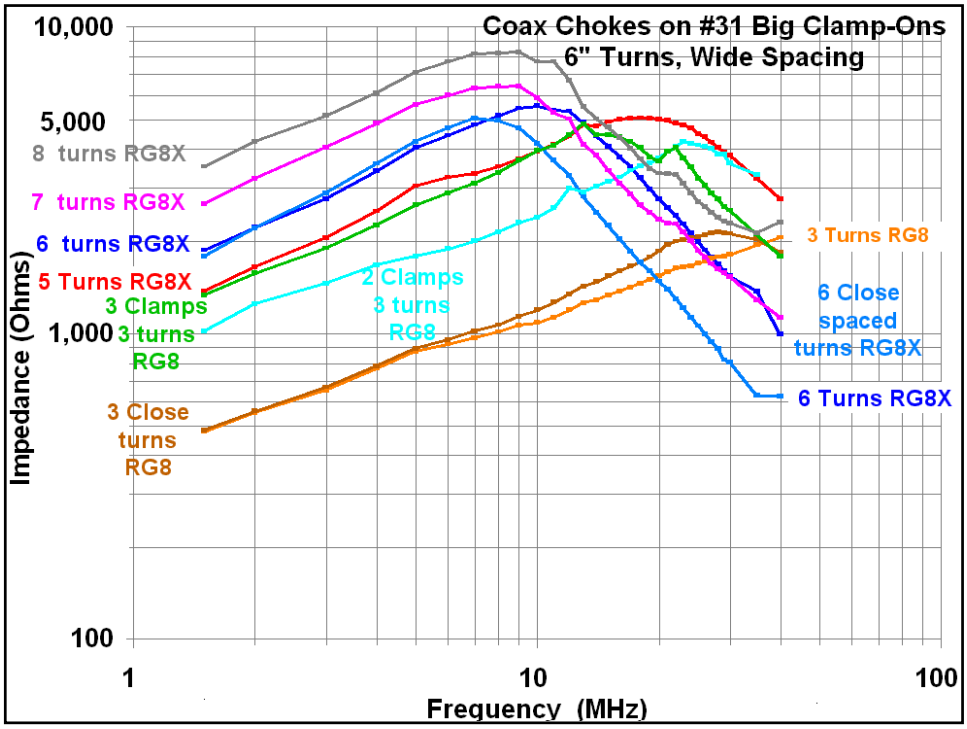


K9YC Chokes (Improvements on W1JR, W2DU Designs)





The "Big Clamp-On" When You Can't Easily Take the Connector Off



If R is Large, What About Heat?

What About Heat?

- Heat (Power) is I^2R
  - Make R large
  - I falls in proportion to R
  - P falls as I^2 so power (heat) is falling twice as fast as R is increasing

What About Heat?

- Heat is not a problem in coax chokes if R (the choking impedance) is large enough
- How large is enough?
  - At maximum ham power, 5,000 Ω allows a very comfortable margin

See K9YC's Choke Cookbook (Chapter 7 in the RFI Tutorial) for specific recommendations

http://audiosystemsgroup.com/RFI-Ham.pdf

How About Commercial Products?

We Can Build At Least as Good As We Can Buy, and for the cost of the cheapies!

- We must stock up on the right parts, buying in quantity

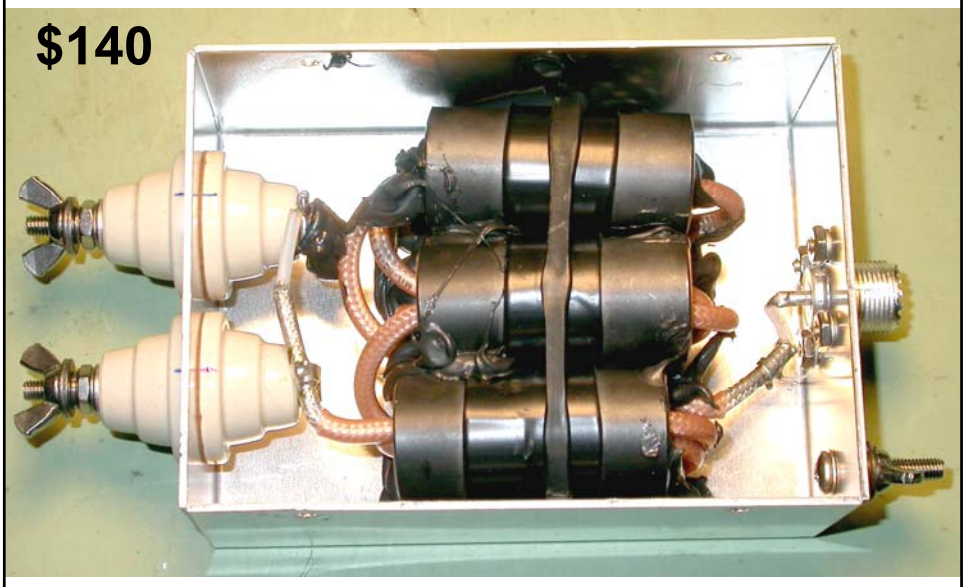
Who Makes Ferrites?

- Most ham ferrite parts are made by Fair-Rite
  - A big family run company in upstate NY
  - She's the EE, he's the Chem Eng
  - Detailed data in catalog on website
- Ham distributors simply resell them
  - Disguised by new part numbers (FT240-61)
  - Very high markups (typically 3-5x cost)
  - Palomar, Amidon, The Wireman
  - Often the "wrong" parts for best performance!

How to Buy Ferrites?

- Get part numbers from my tutorial
  - http://audiosystemsgroup.com/RFI-Ham.pdf
- Buy in quantity from distributors listed on the Fair-Rite website
  - Newark, Allied, Lodestone Pacific, Kreger
- Buy in large quantities direct from Fair-Rite
- Don't be a cheap ham
  - Think big – it costs more to think small!
  - Spend your money wisely

DX Engineering 50Ω Choke Balun

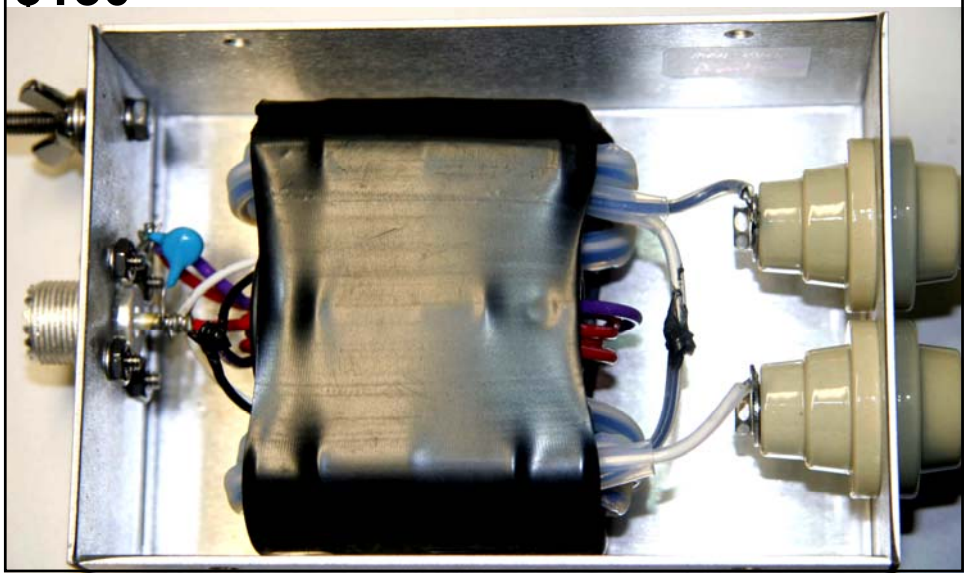


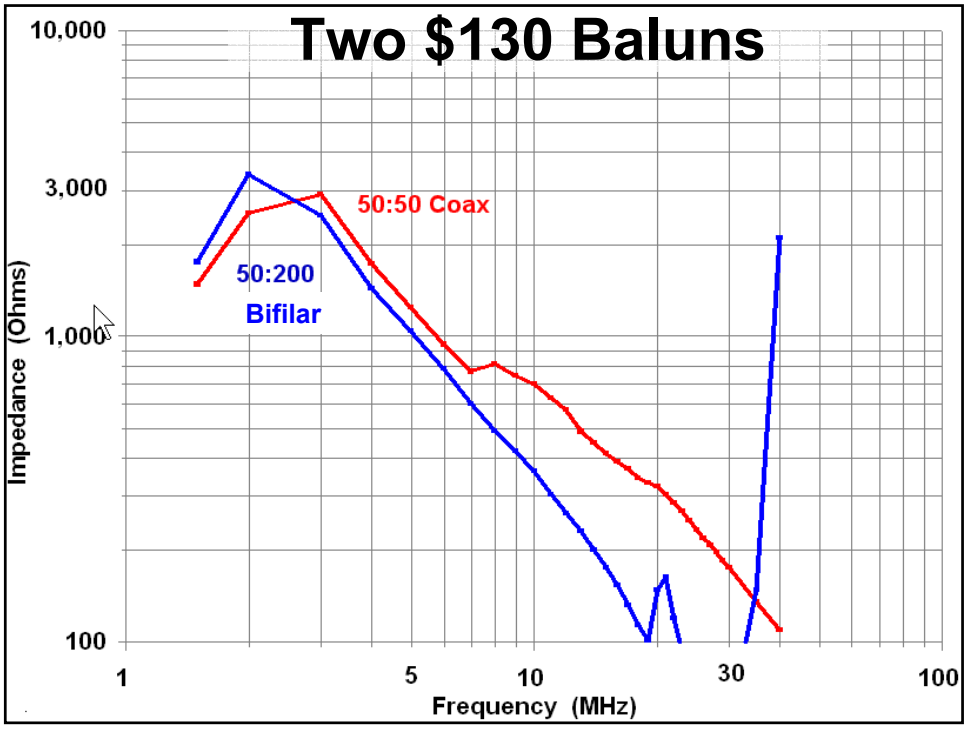
DX Engineering 200Ω – 50Ω Bifilar Choke Balun

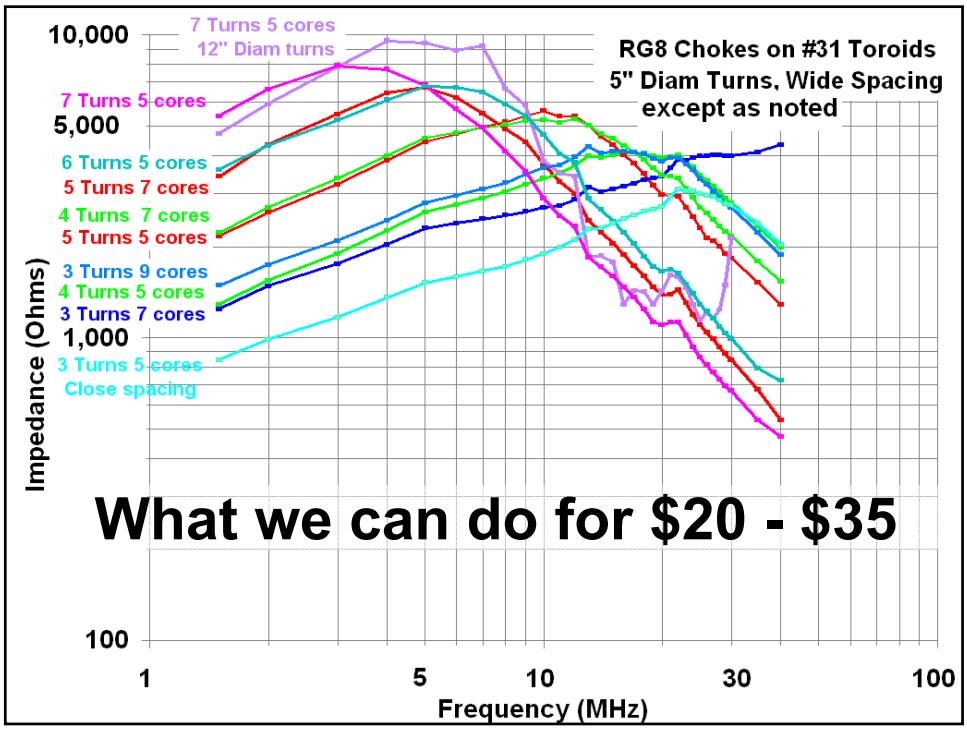
$130

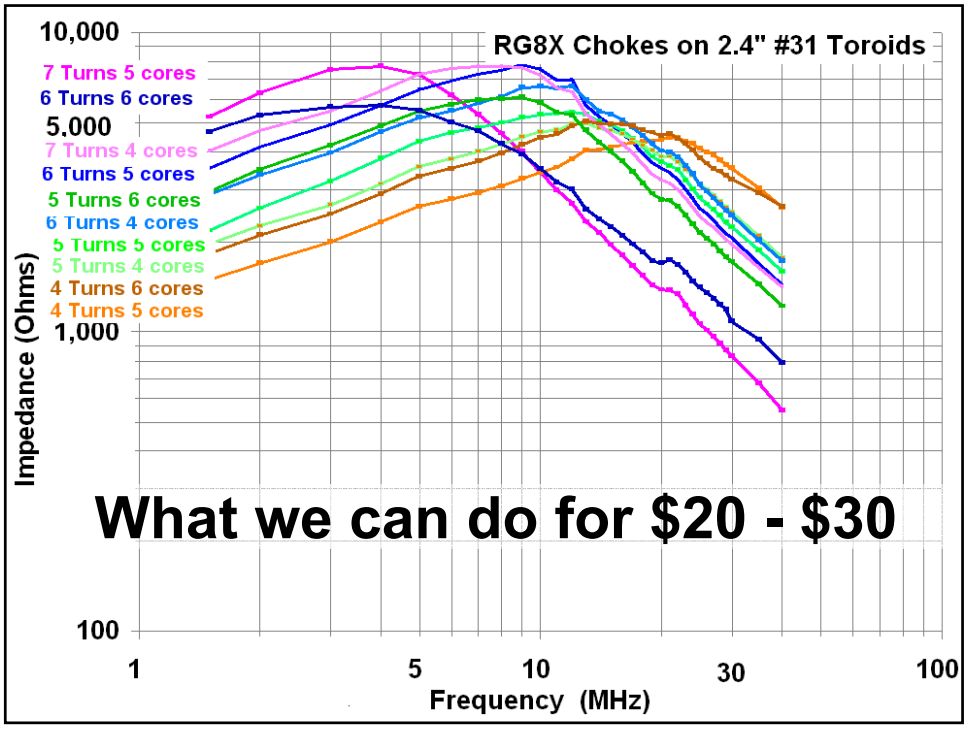
DX Engineering 300Ω – 50Ω Bifilar Choke Balun

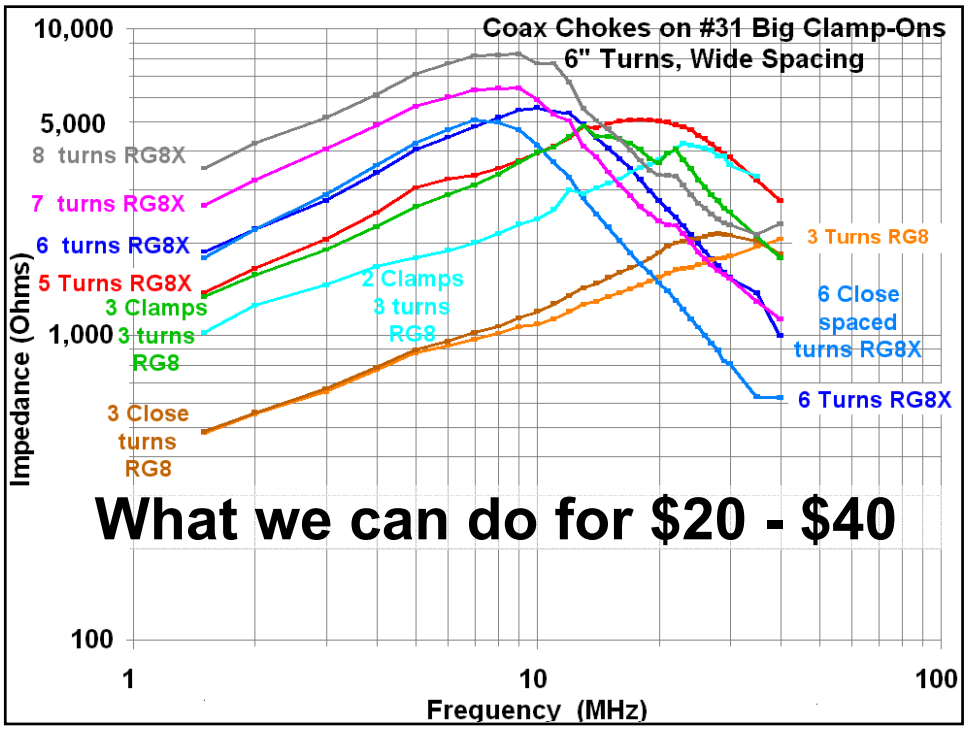
$130




Two $130 Baluns
10,000
3,000
1,000
100
Impedance (Ohms)
50:50 Coax
50:200
Bifilar
1
5
10
30
100
Frequency (MHz)


10,000
5,000
1,000
100
Impedance (Ohms)
7 Turns 5 cores
12" Diam turns
7 Turns 5 cores
6 Turns 5 cores
5 Turns 7 cores
4 Turns 7 cores
5 Turns 5 cores
3 Turns 9 cores
4 Turns 5 cores
3 Turns 7 cores
3 Turns 5 cores
Close spacing
RG8 Chokes on #31 Toroids
5" Diam Turns, Wide Spacing
except as noted
What we can do for $20 - $35
1
5
10
30
100
Frequency (MHz)

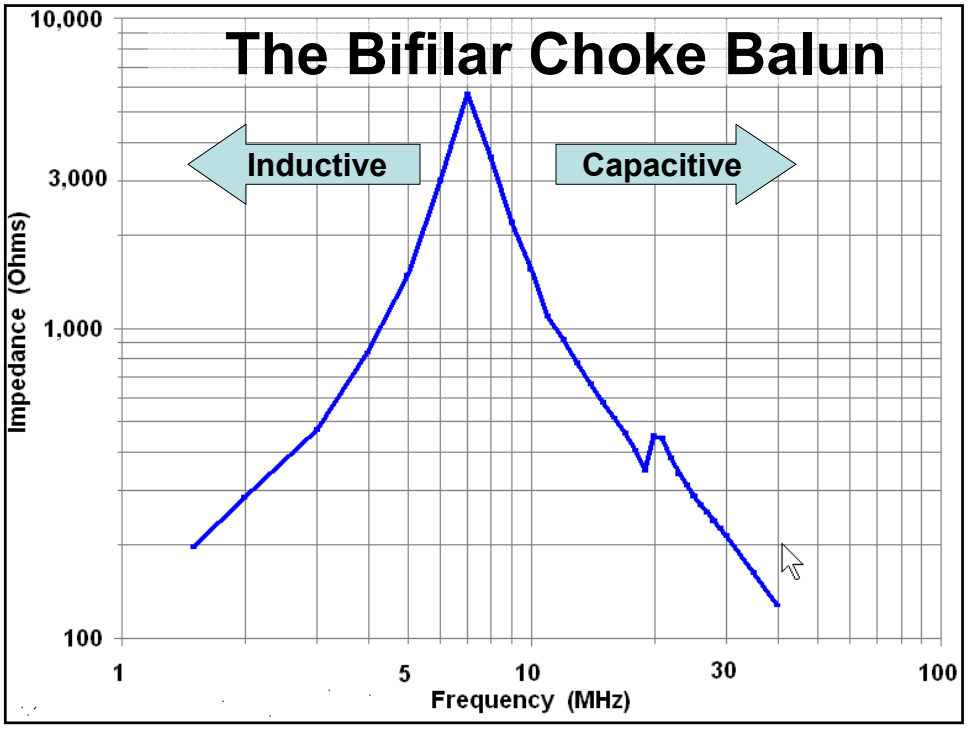

RG8X Chokes on 2.4" #31 Toroids
10,000
5,000
1,000
100
Impedance (Ohms)
7 Turns 5 cores
6 Turns 6 cores
7 Turns 4 cores
6 Turns 5 cores
5 Turns 6 cores
6 Turns 4 cores
5 Turns 5 cores
5 Turns 4 cores
4 Turns 6 cores
4 Turns 5 cores
What we can do for $20 - $30
1
5
10
30
100
Frequency (MHz)


Coax Chokes on #31 Big Clamp-Ons
6" Turns, Wide Spacing
10,000
5,000
1,000
100
Impedance (Ohms)
8 turns RG8X
7 turns RG8X
6 turns RG8X
5 Turns RG8X
3 Clamps
3 turns
RG8
3 Close
turns
RG8
2 Clamps
3 turns
RG8
3 Turns RG8
6 Close
spaced
turns RG8X
6 Turns RG8X
What we can do for $20 - $40
1
10
100
Frequency (MHz)

See K9YC's Choke Cookbook (Chapter 7 in the RFI Tutorial) for specific recommendations

http://audiosystemsgroup.com/RFI-Ham.pdf

Bifilar Choke Balun on low loss core (Discontinued by DX Engineering)



Twin Lead Still Needs a Choke

- Remember those unbalanced antennas fed with balanced line?
  - We still must choke them to kill receive noise, feedline radiation, and RF in the shack
  - But they're not easy to choke effectively

Twin Lead and Bifilar Windings – Two Heads of the Same Snake!

- The problem is ***leakage flux***
  - Causes heating in a lossy core
  - Must use low loss core
  - Low loss means it's narrow band, and is reactive away from resonance
  - Sensitive to feedline length
  - How do you wind a twin lead choke?

Twin Lead and Bifilar Windings – Two Heads of the Same Snake!

- Because of leakage flux:
  - Much more likely to overheat
  - Core more likely to saturate (harmonics, IMD, splatter, choking impedance drops)
- All-band antennas fed with twinlead can work, but this is another of the compromises!

Wide or Close Spaced Turns?

- Close spacing lowers resonant frequency
  - More capacitance
  - More inductance
- Close spacing often better below 10 MHz
- Wide spacing usually best above 10 MHz
- Study the K9YC data and Cookbook for specific applications

An 80/40 Fan Dipole

Closely Spaced Turns for an 80/40 Fan Dipole

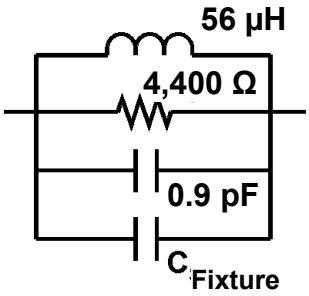
The Measurement Problem

Measuring Coax Chokes

- Very difficult to measure
- Traditional "reflection" measurements give wrong results
  - Poor accuracy if 5 ohms > Zx > 500 ohms
- Stray capacitance of fixture causes additional errors
  - Some VNA's and other analyzers that claim to subtract it out <u>don't</u>
- **A lot of smart people have missed all this!**

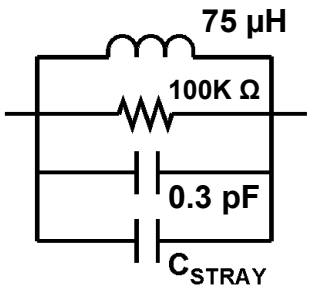
What are we Trying to Measure?

#31



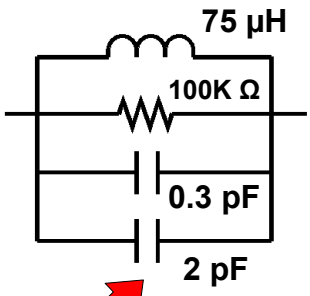
What are we Trying to Measure?

#61



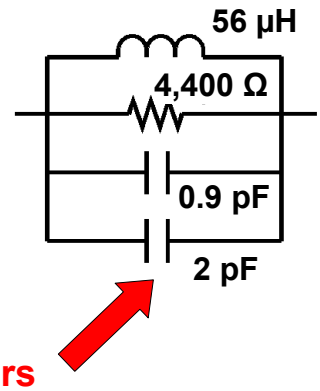
What are we Trying to Measure?

#61



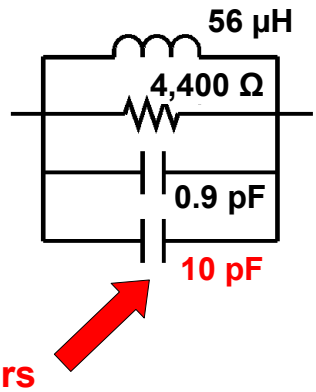
Typical "good" analyzers

What are we Trying to Measure?



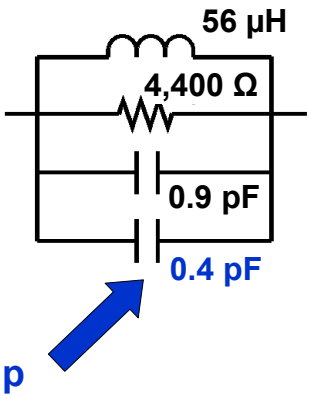
Typical "good" analyzers

What are we Trying to Measure?

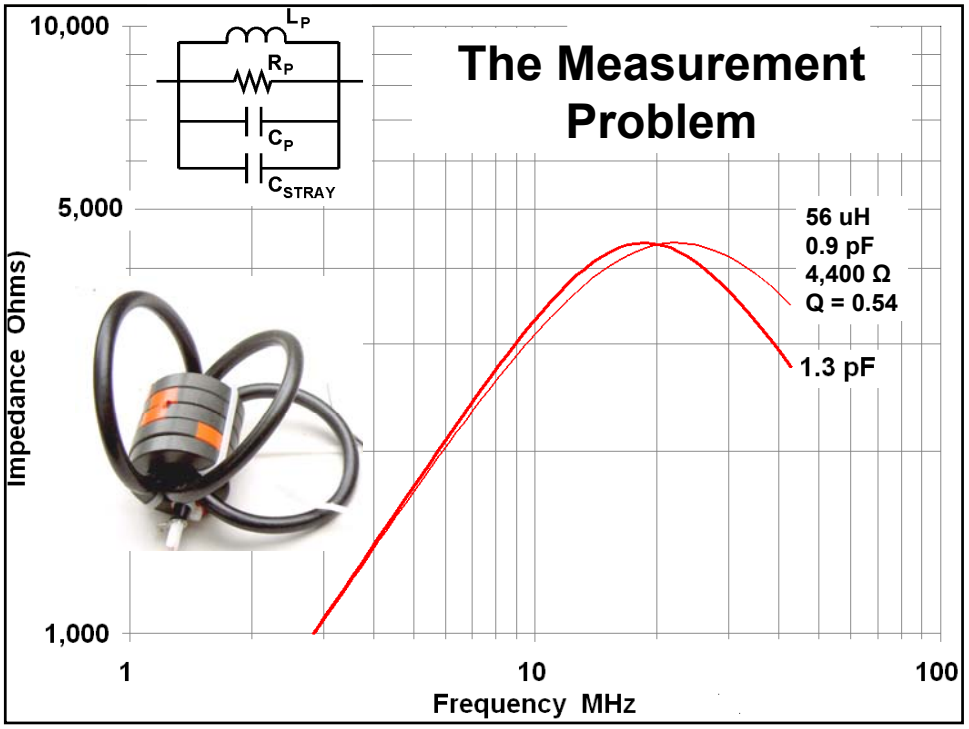


Typical "antenna" analyzers

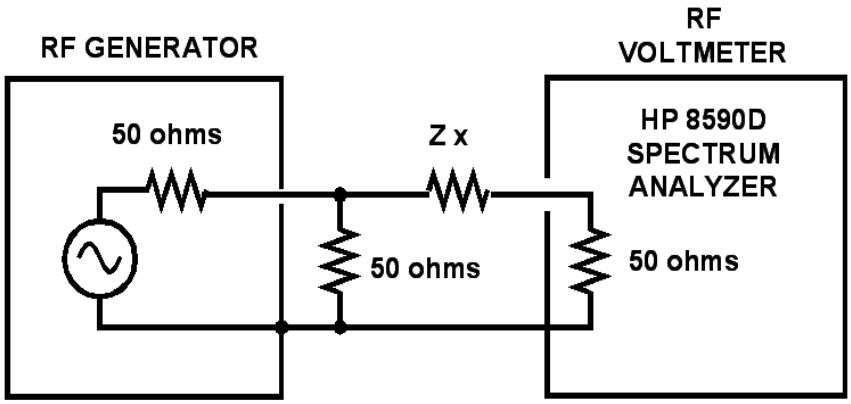
What are we Trying to Measure?

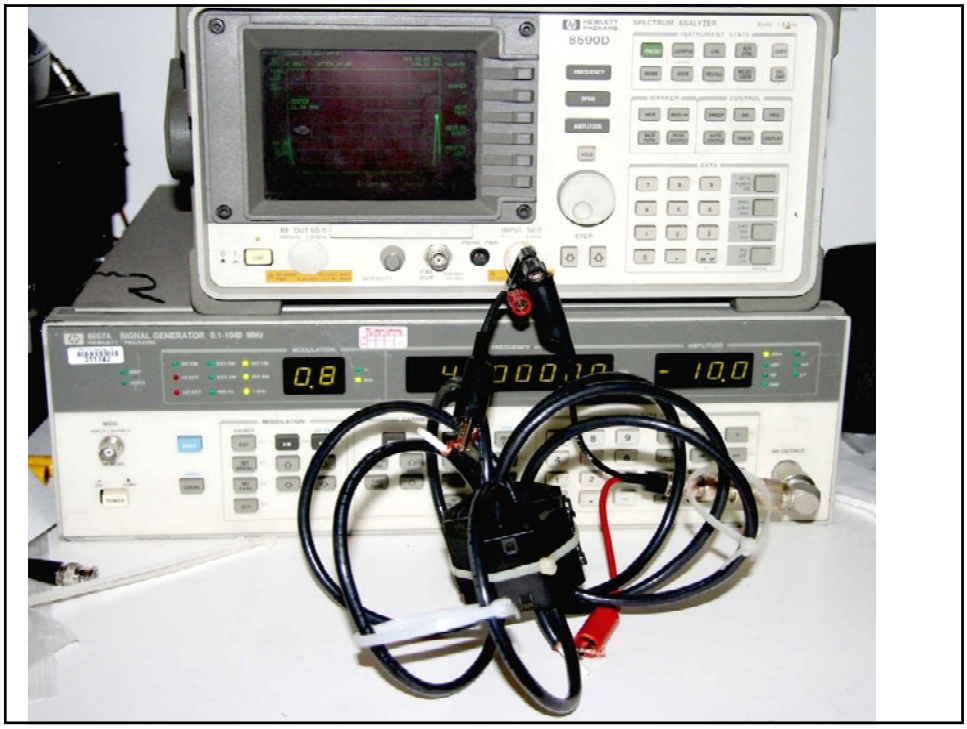


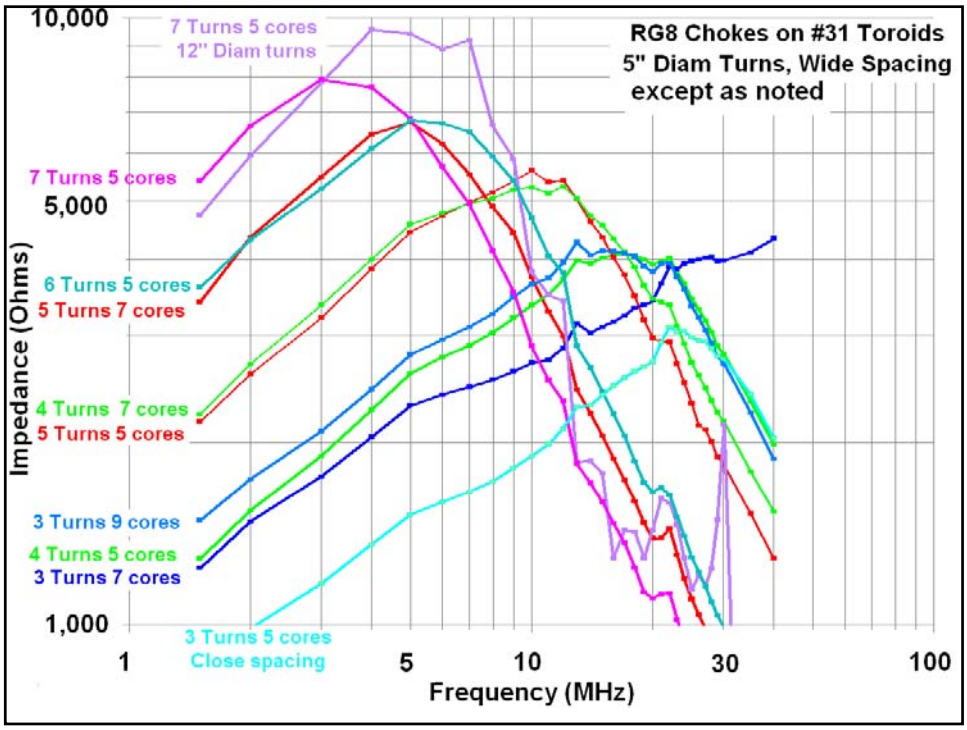
My measurement setup

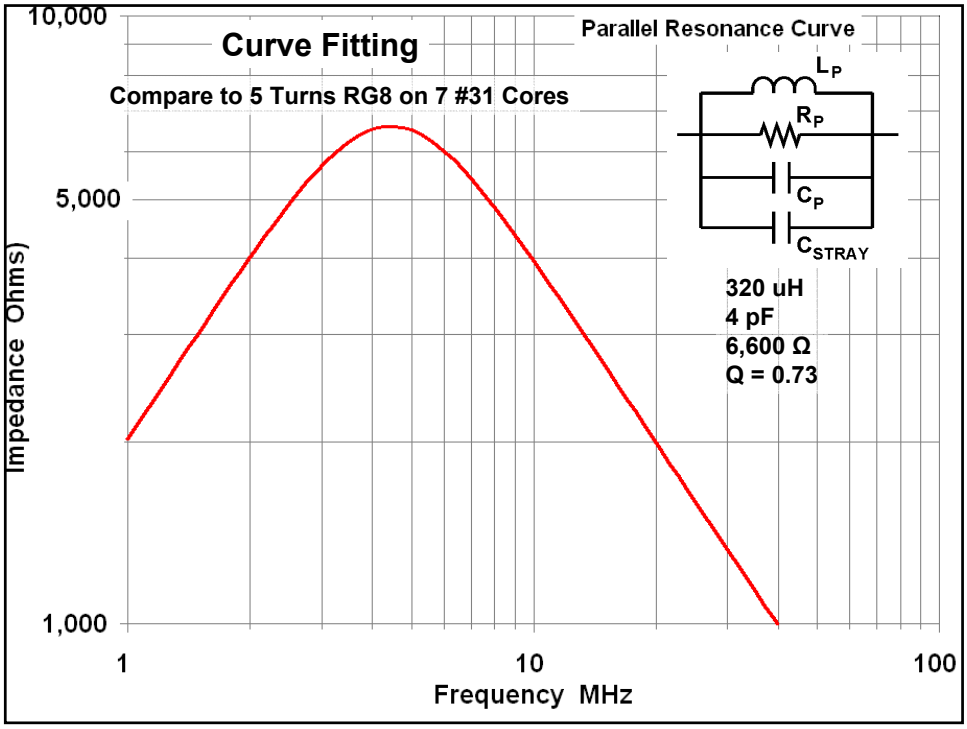


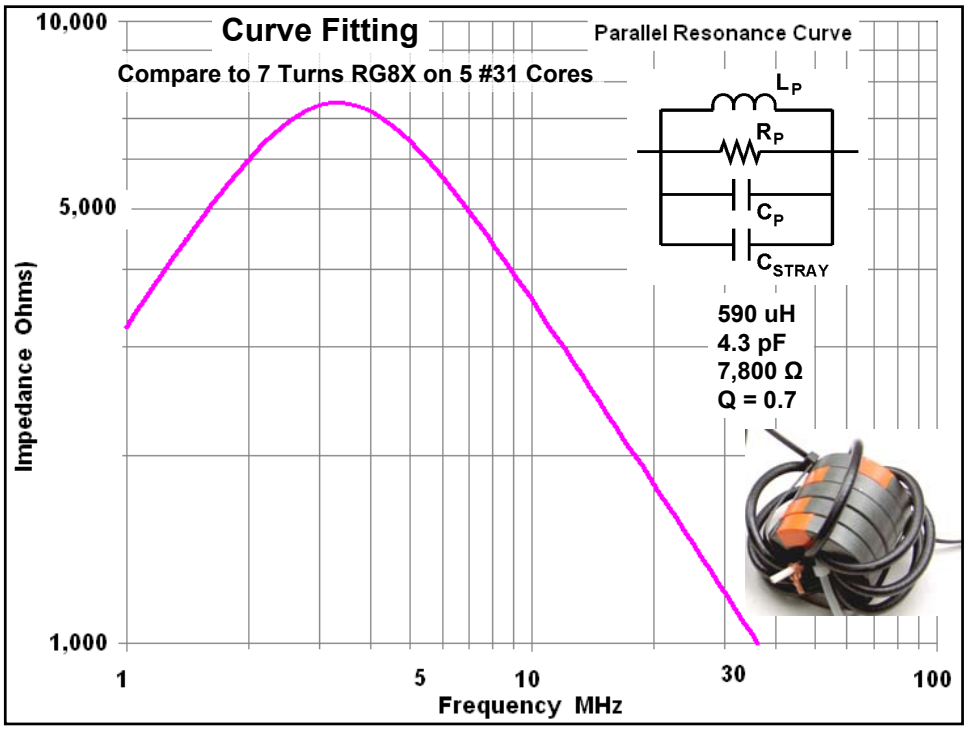
Measuring Coax Chokes

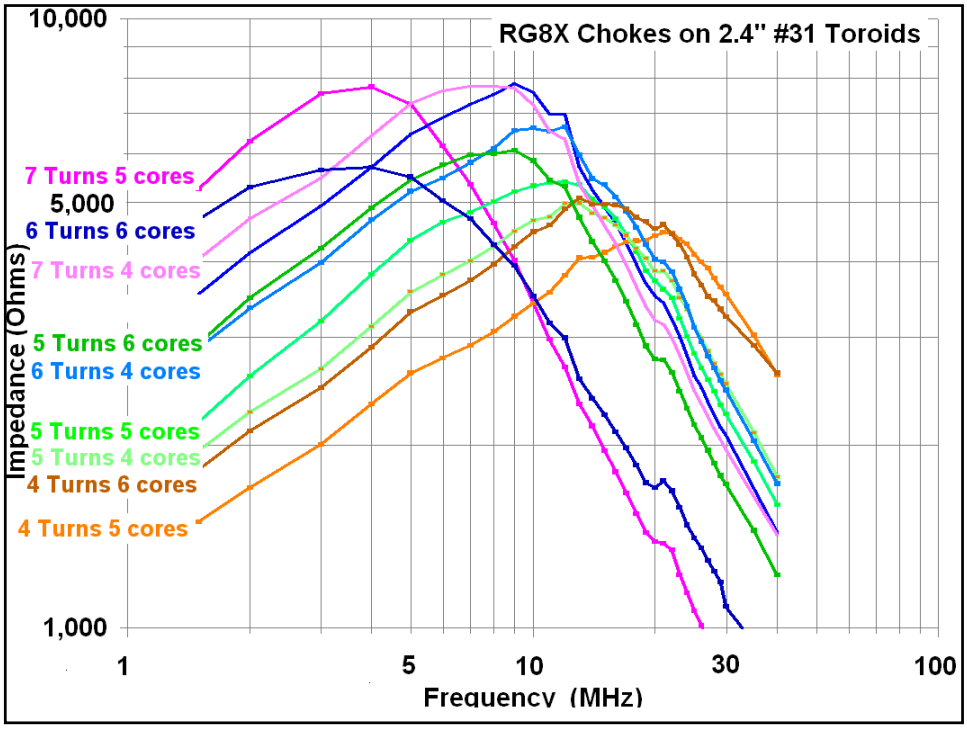


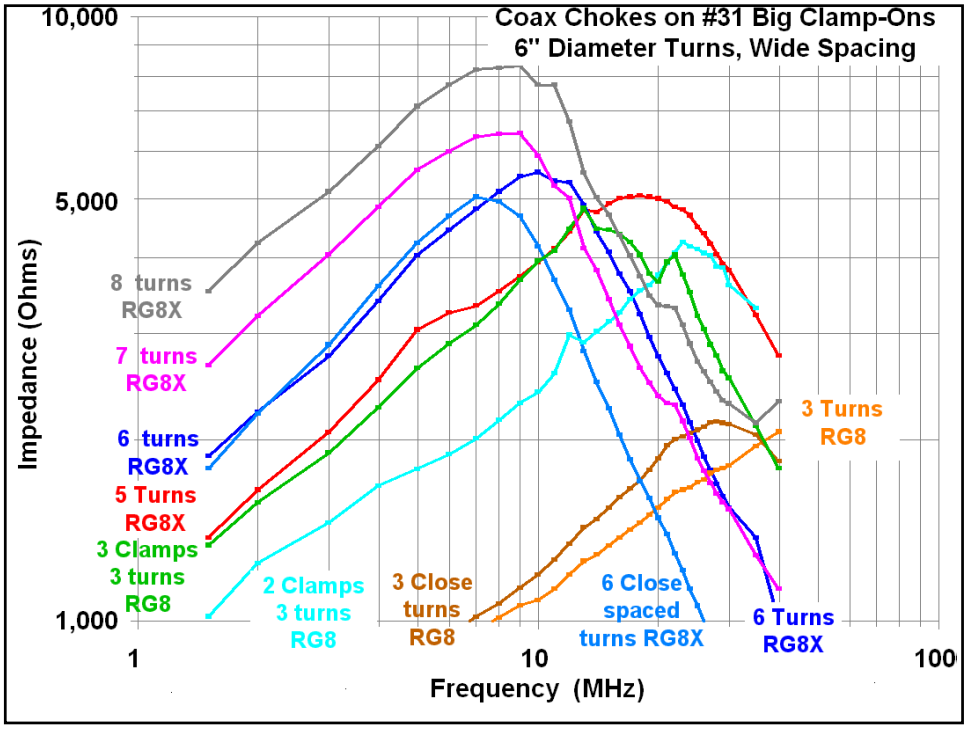


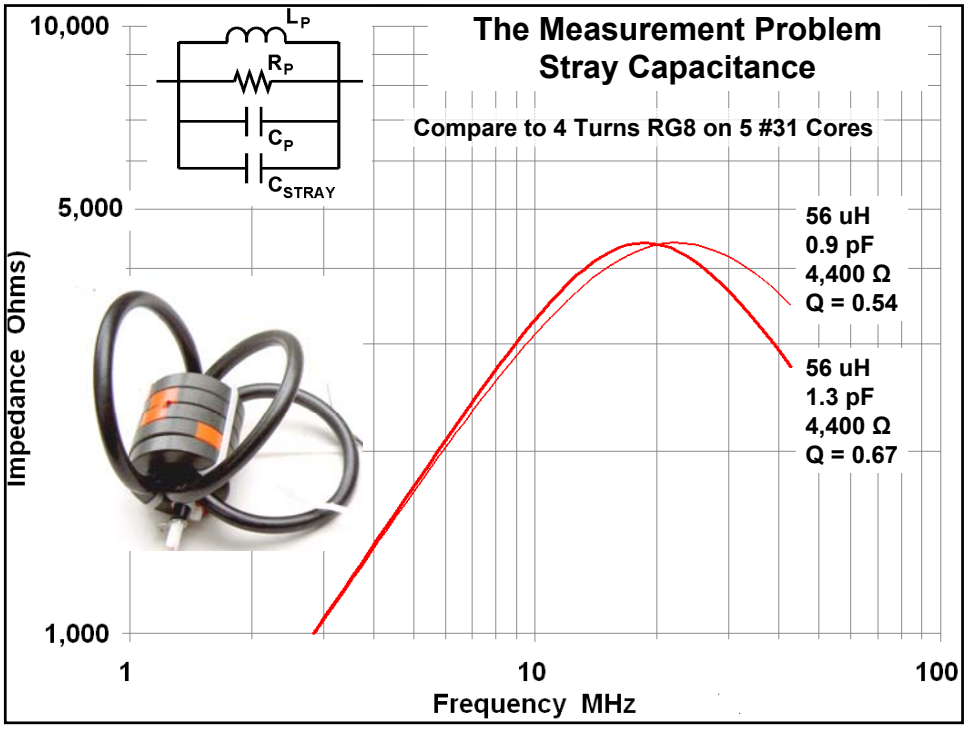

RG8 Chokes on #31 Toroids
5" Diam Turns, Wide Spacing
except as noted
10,000
5,000
1,000
Impedance (Ohms)
7 Turns 5 cores
12" Diam turns
7 Turns 5 cores
6 Turns 5 cores
5 Turns 7 cores
4 Turns 7 cores
5 Turns 5 cores
3 Turns 9 cores
4 Turns 5 cores
3 Turns 7 cores
3 Turns 5 cores
Close spacing
1
5
10
30
100
Frequency (MHz)

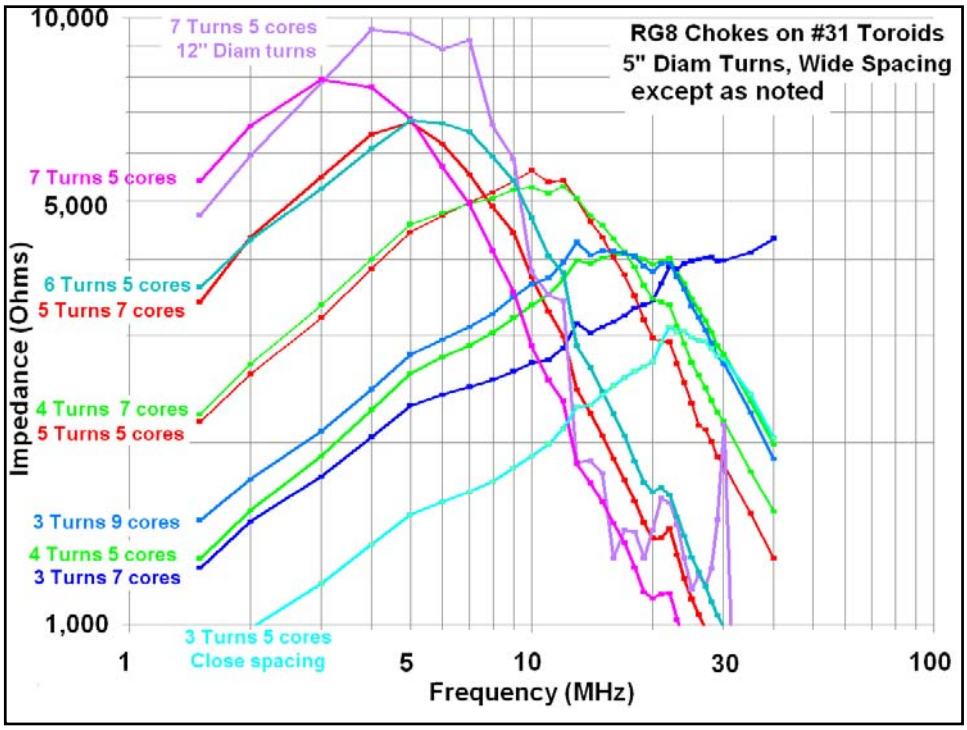

Curve Fitting
Compare to 5 Turns RG8 on 7 #31 Cores
Parallel Resonance Curve
L_P
R_P
C_P
C_{STRAY}
320 uH
4 pF
6,600 Ω
Q = 0.73
10,000
5,000
1,000
Impedance Ohms)
1
10
100
Frequency MHz


Curve Fitting
Compare to 7 Turns RG8X on 5 #31 Cores
Parallel Resonance Curve
L_P
R_P
C_P
C_{STRAY}
590 uH
4.3 pF
7,800 Ω
Q = 0.7
10,000
5,000
1,000
Impedance Ohms)
1
5
10
30
100
Frequency MHz

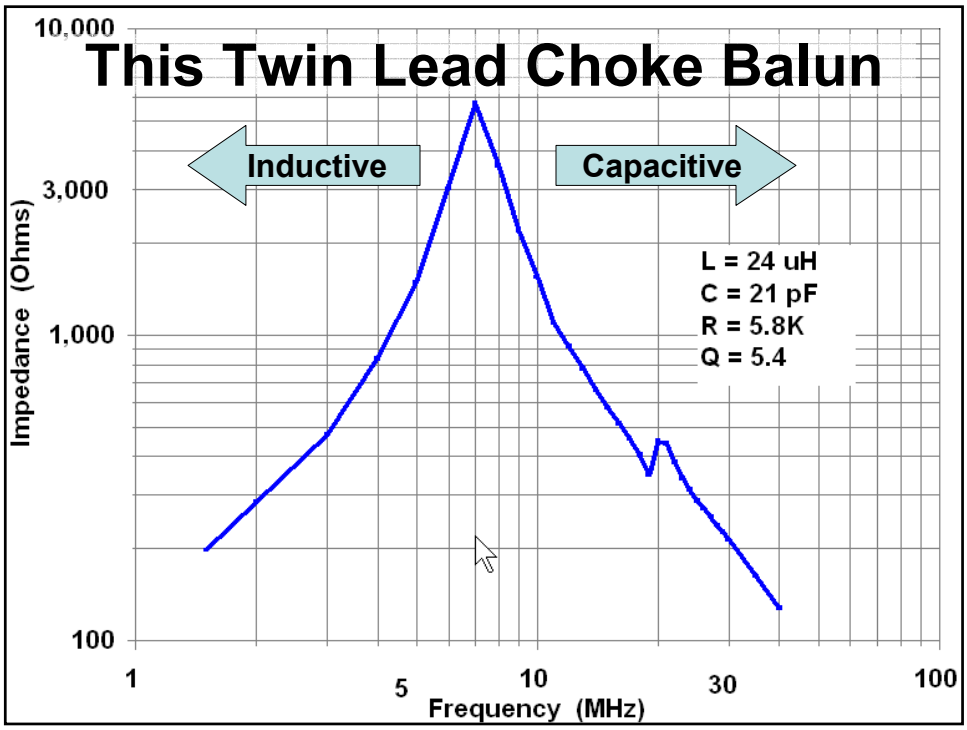

RG8X Chokes on 2.4" #31 Toroids
10,000
5,000
1,000
Impedance (Ohms)
7 Turns 5 cores
6 Turns 6 cores
7 Turns 4 cores
5 Turns 6 cores
6 Turns 4 cores
5 Turns 5 cores
5 Turns 4 cores
4 Turns 6 cores
4 Turns 5 cores
1
5
10
30
100
Frequency (MHz)


Coax Chokes on #31 Big Clamp-Ons
6" Diameter Turns, Wide Spacing
10,000
5,000
1,000
Impedance (Ohms)
8 turns RG8X
7 turns RG8X
6 turns RG8X
5 Turns RG8X
3 Clamps 3 turns RG8
2 Clamps 3 turns RG8
3 Close turns RG8
6 Close spaced turns RG8X
6 Turns RG8X
3 Turns RG8
1
10
100
Frequency (MHz)


The Measurement Problem
Stray Capacitance
Compare to 4 Turns RG8 on 5 #31 Cores
L_P
R_P
C_P
C_{STRAY}
10,000
5,000
1,000
Impedance Ohms)
1
10
100
Frequency MHz
56 uH
0.9 pF
4,400 Ω
Q = 0.54
56 uH
1.3 pF
4,400 Ω
Q = 0.67

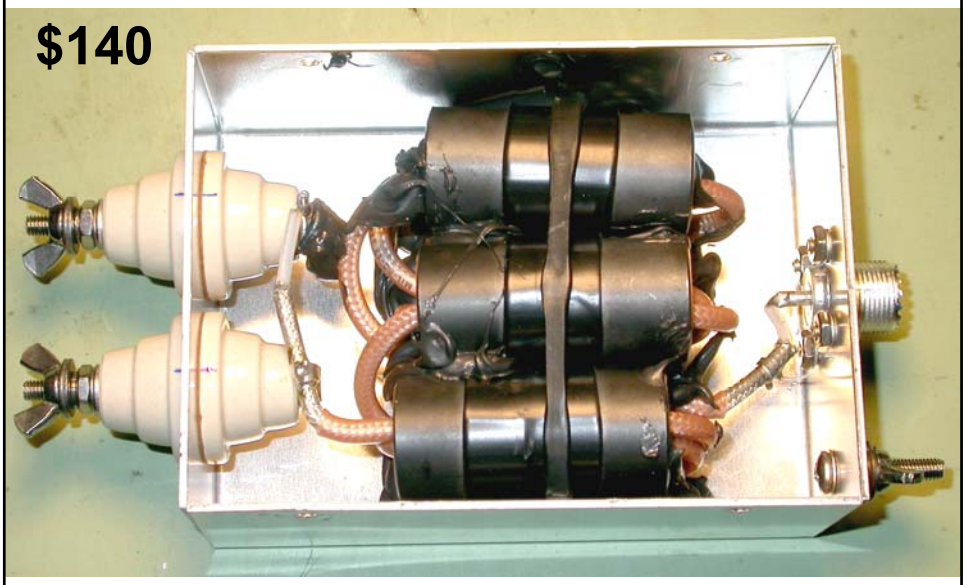

RG8 Chokes on #31 Toroids
5" Diam Turns, Wide Spacing
except as noted
7 Turns 5 cores
12" Diam turns
7 Turns 5 cores
6 Turns 5 cores
5 Turns 7 cores
4 Turns 7 cores
5 Turns 5 cores
3 Turns 9 cores
4 Turns 5 cores
3 Turns 7 cores
3 Turns 5 cores
Close spacing
10,000
5,000
1,000
Impedance (Ohms)
1
5
10
30
100
Frequency (MHz)

Bifilar Choke Balun on low loss core (Discontinued by DX Engineering)



DX Engineering 50Ω Choke Balun

$140

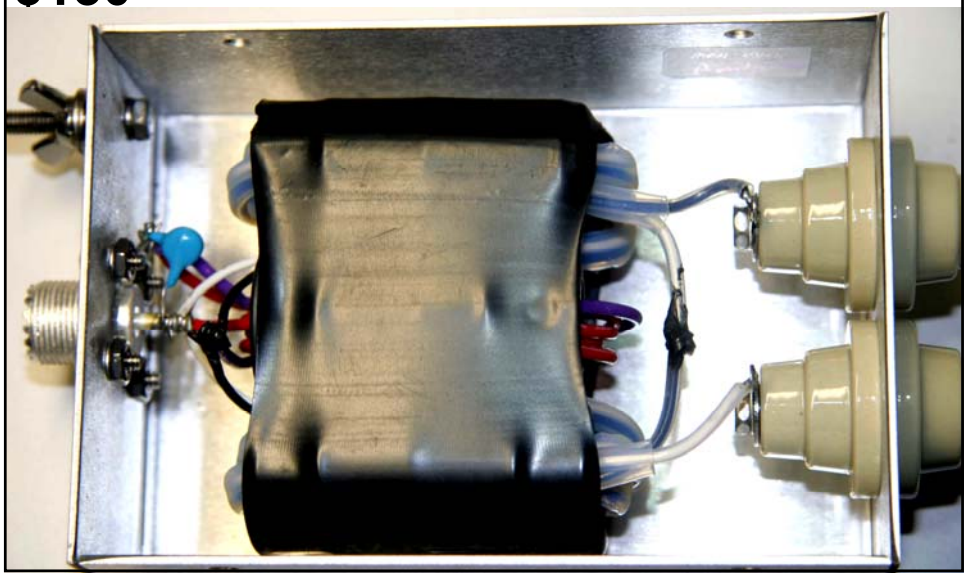


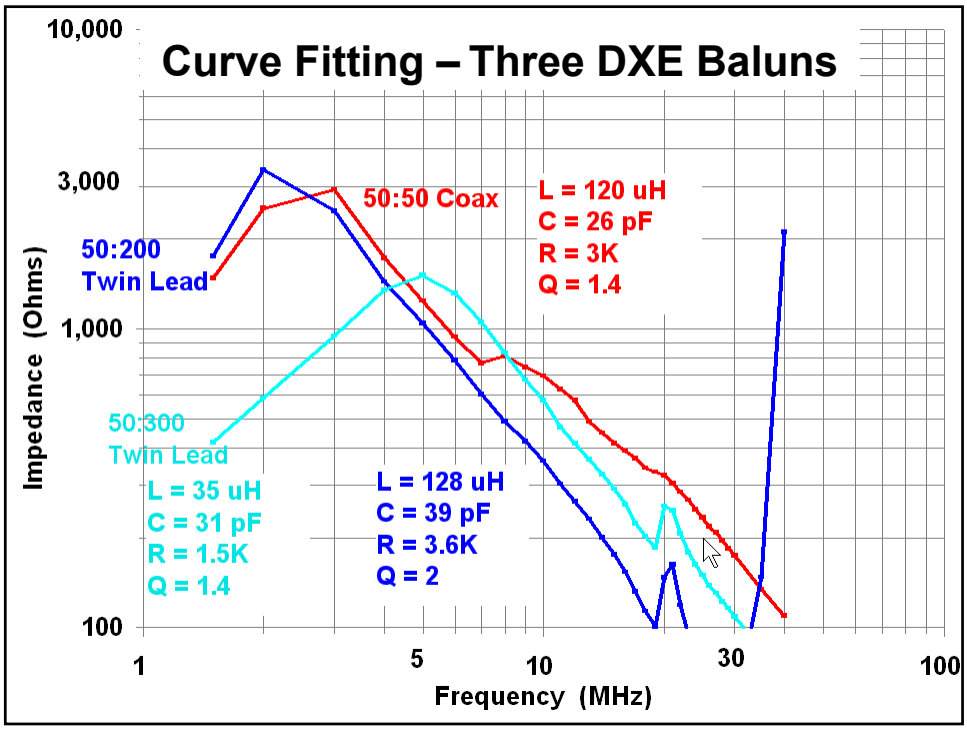
DX Engineering 200Ω – 50Ω Twin Lead Choke Balun

$130

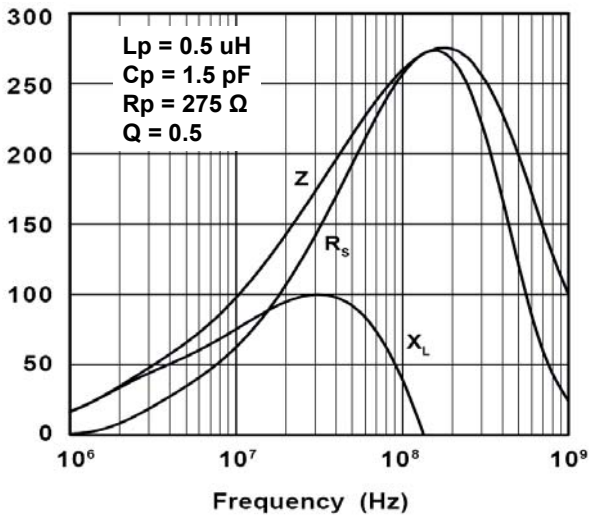
DX Engineering 300Ω – 50Ω Twin Lead Choke Balun

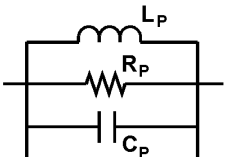
$130





Curve Fitting – #31 HF-VHF Clamp-On Fair-Rite 0431164281





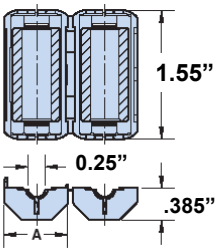
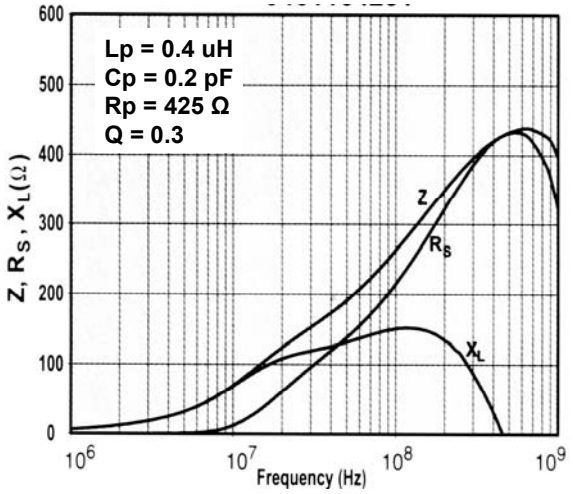
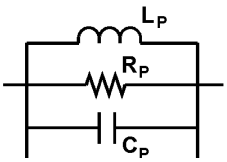


Figure 1

Curve Fitting – #61 UHF Clamp-On Fair-Rite 0461164281





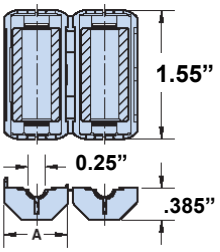
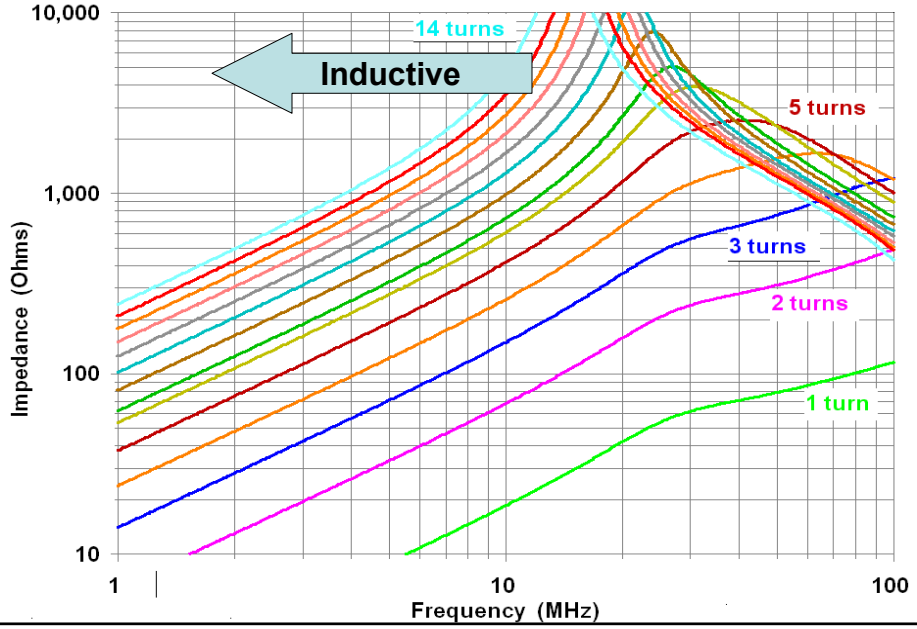
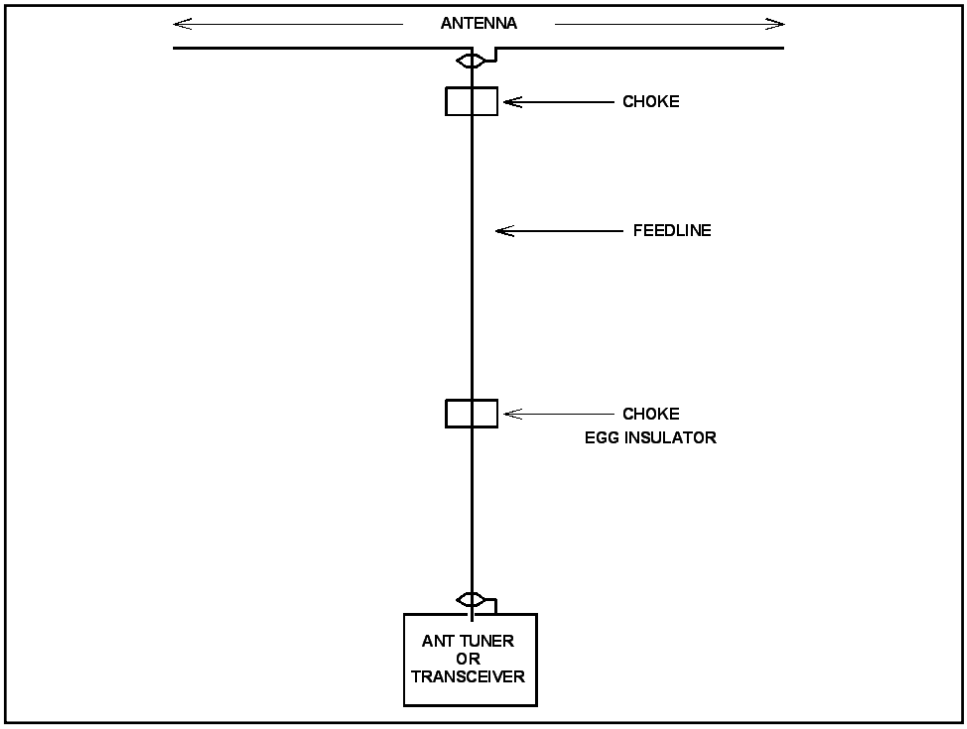


Figure 1

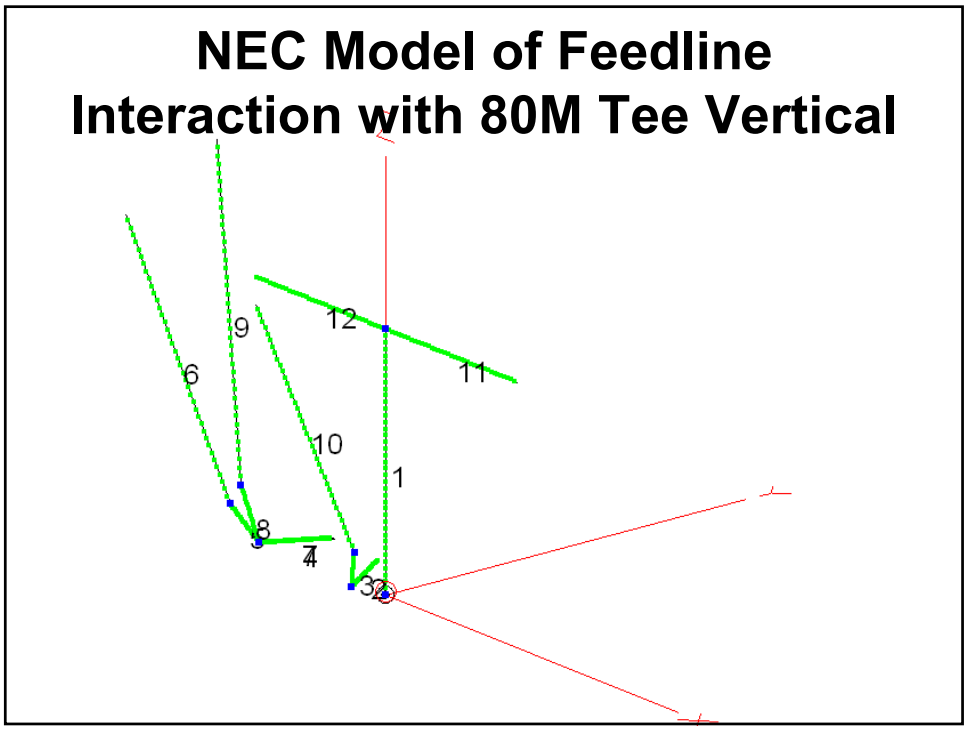
Small Wire Chokes on a #61 toroid



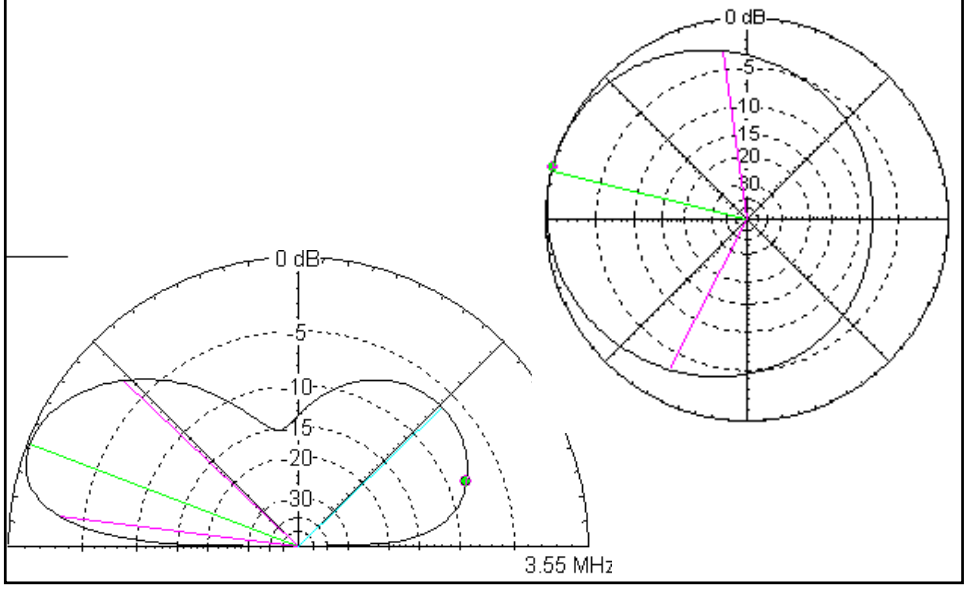
Chokes as “Egg Insulators to Break Up the Feedline



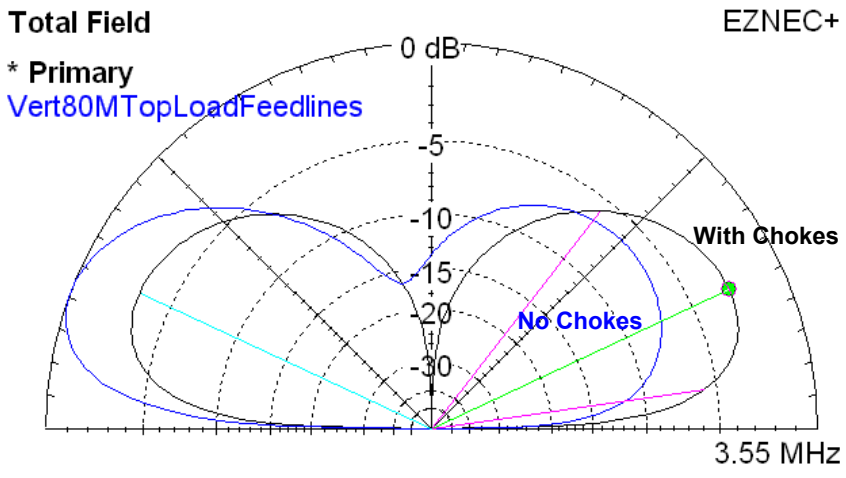
NEC Model of Feedline Interaction with 80M Tee Vertical



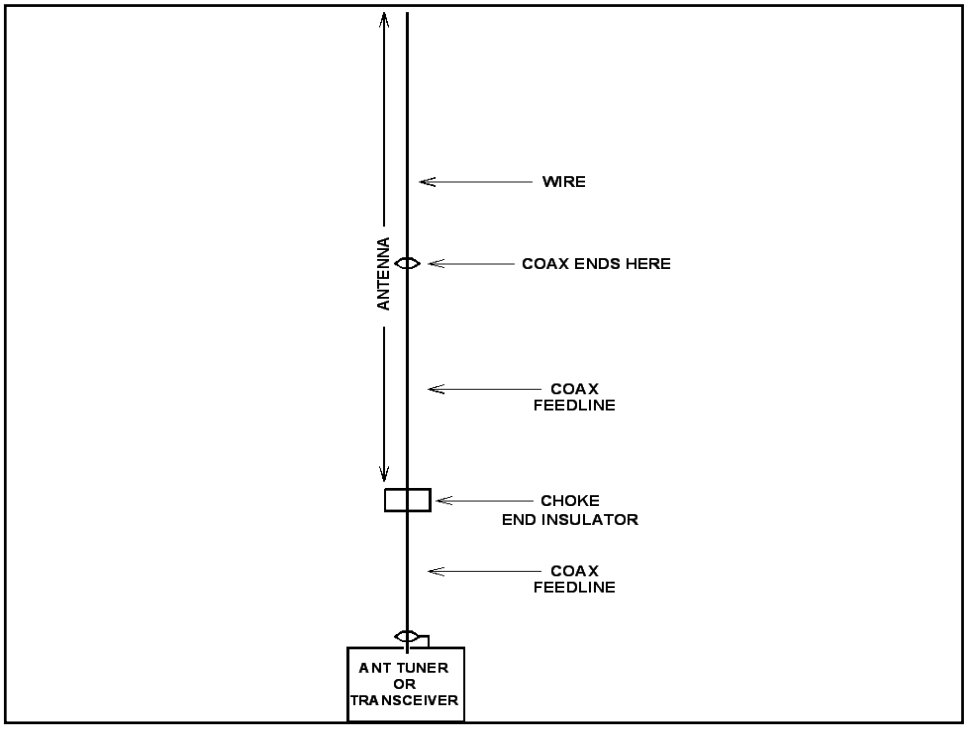
NEC Model of Feedline Interaction with Tee Vertical

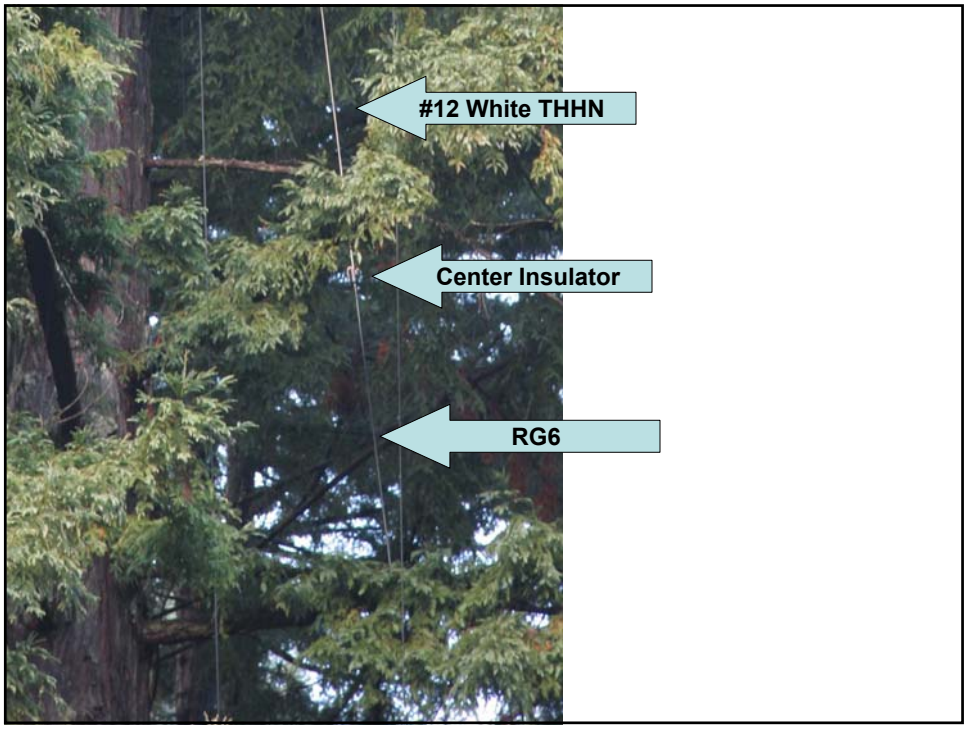


Add Choke in Each Feedline



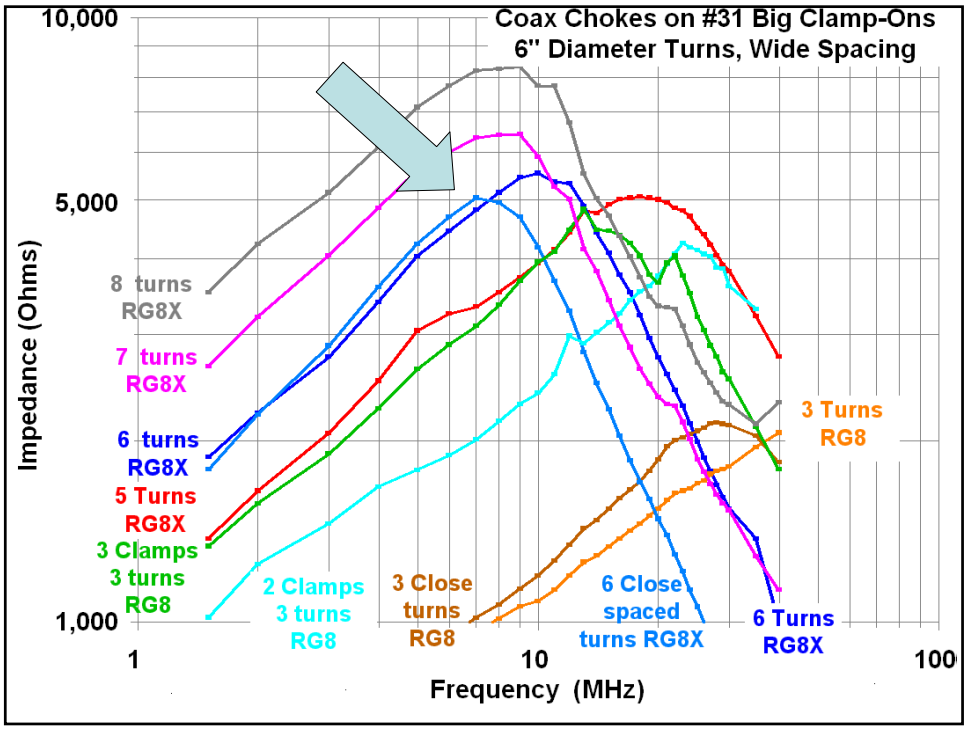
A Choke as the End Insulator of a Vertical Dipole


WIRE
ANTENNA
COAX ENDS HERE
COAX
FEEDLINE
CHOKE
END INSULATOR
COAX
FEEDLINE
ANT TUNER
OR
TRANSCEIVER

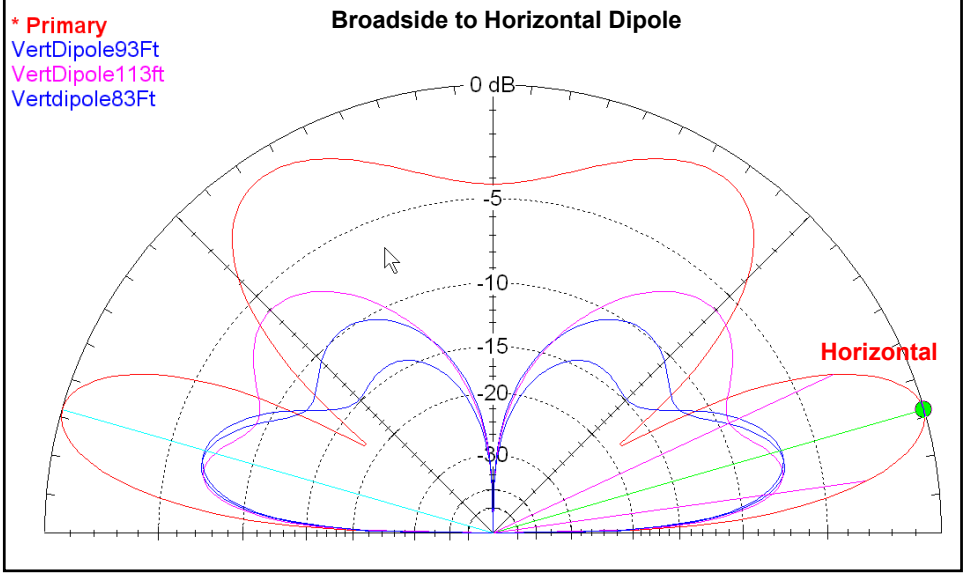


End Insulator for a 40M Dipole

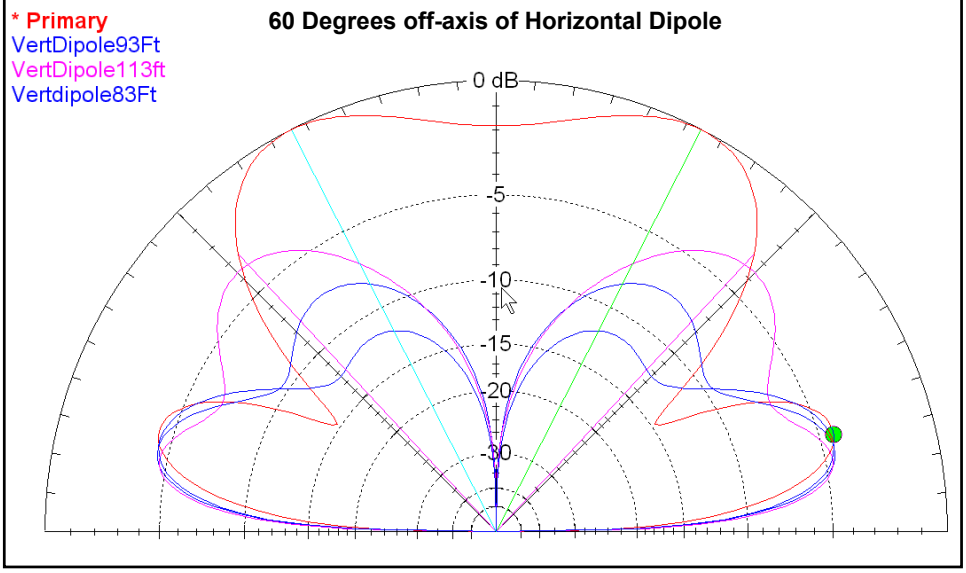
- 6 turns of RG6 around a “big clamp-on” is enough for 500 watts of serious contesting
  - About 5,000Ω resistive impedance
- Two of these 6-turn chokes are needed for 1.5kW
  - About 10,000Ω resistive impedance


Coax Chokes on #31 Big Clamp-Ons
6" Diameter Turns, Wide Spacing
10,000
5,000
1,000
Impedance (Ohms)
1
10
100
Frequency (MHz)
8 turns RG8X
7 turns RG8X
6 turns RG8X
5 Turns RG8X
3 Clamps 3 turns RG8
2 Clamps 3 turns RG8
3 Close turns RG8
6 Close spaced turns RG8X
6 Turns RG8X
3 Turns RG8

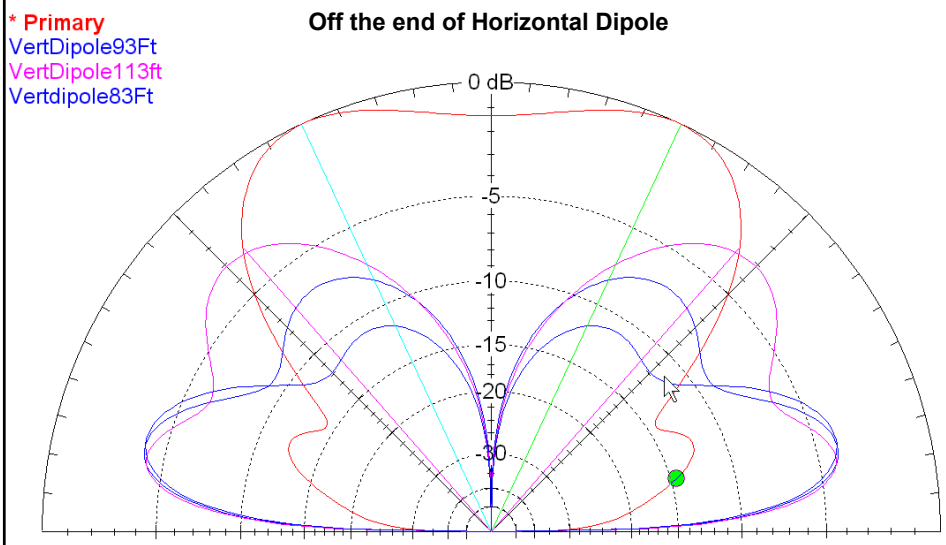
Before you fall in love with a vertical dipole, compare it to a horizontal dipole!



Before you fall in love with a vertical dipole, compare it to a horizontal dipole!

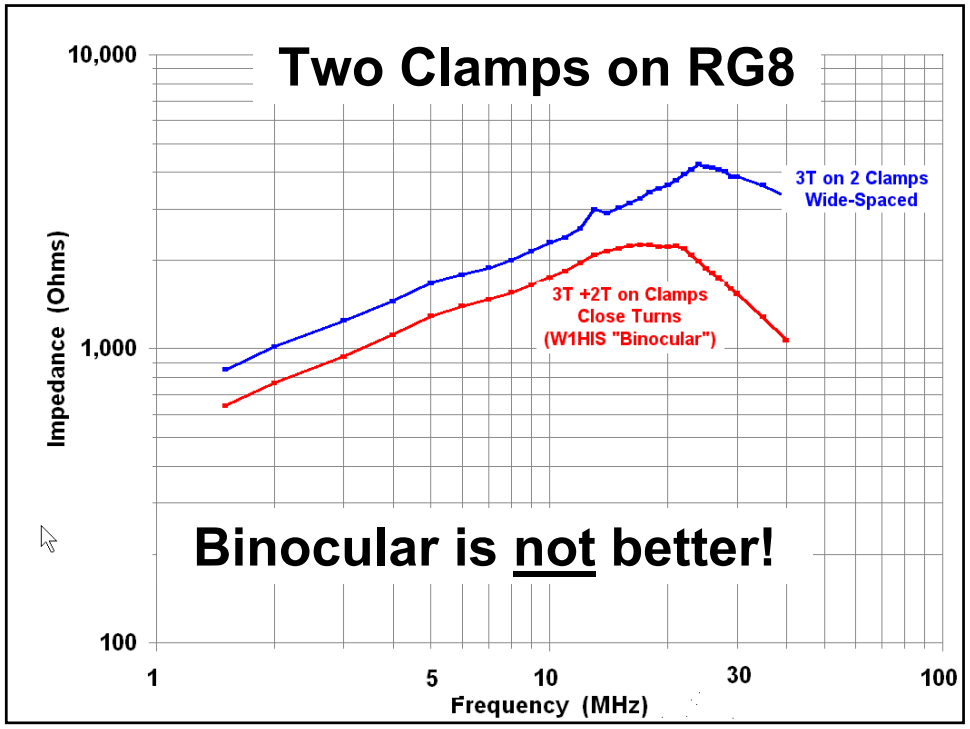


Before you fall in love with a vertical dipole, compare it to a horizontal dipole!



W1HIS Coaxial Choke

#43 cores

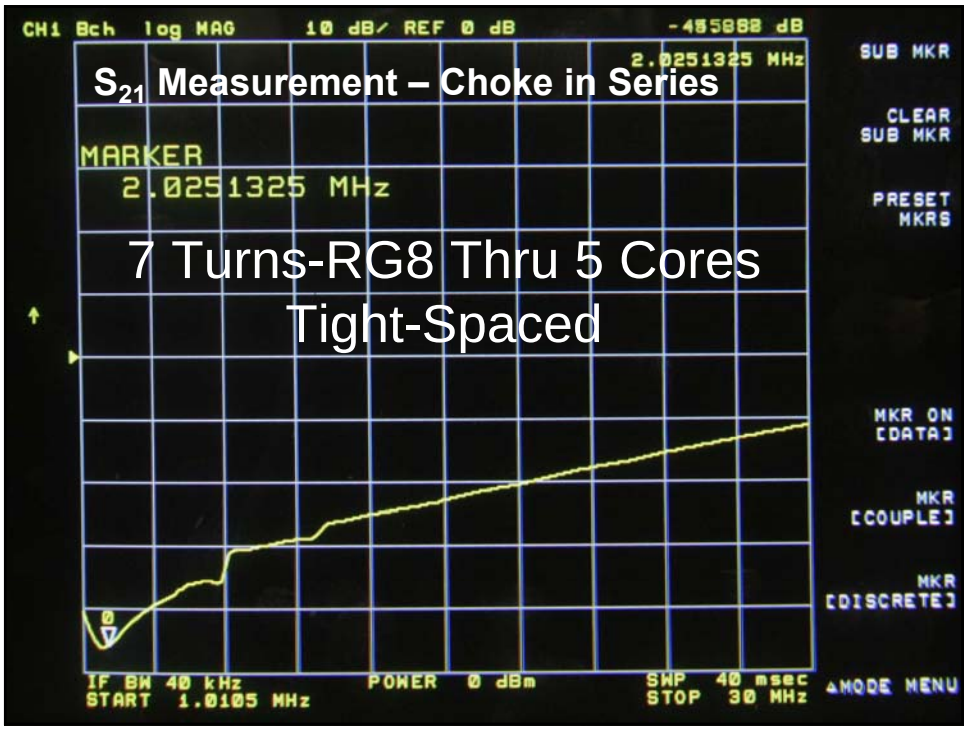


Thanks to Kevin, K6TD

- Helped me verify my suspicions about reflection-based measurements, and get good S21 data using his HP Network Analyzer

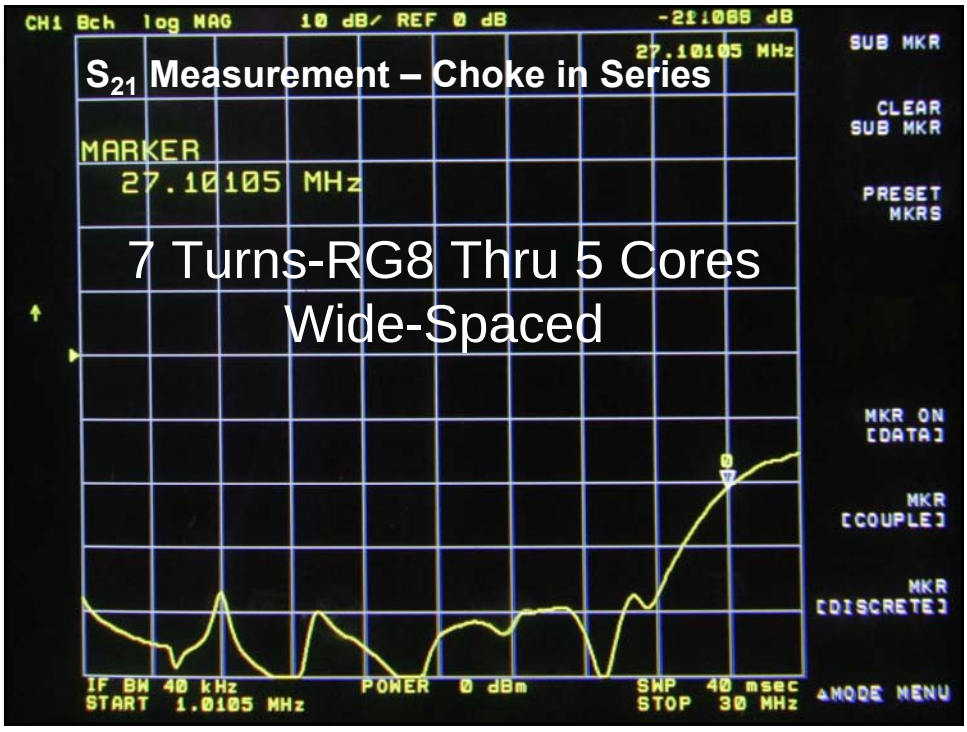
  (Unfortunately, we didn't have the extra hardware needed to get complex data out of the analyzer into a spreadsheet.)

7 Turns-RG8 Thru 5 Cores Tight-Spaced



S_{21} Measurement – Choke in Series

7 Turns-RG8 Thru 5 Cores Wide-Spaced



S_{21} Measurement – Choke in Series

7 Turns-RG8 Thru 5 Cores Wide-Spaced

Thanks to Chuck, W1HIS

- Chuck was right about using 5,000Ω chokes to minimize receive noise
- Chuck was wrong about how to build 5,000Ω chokes, because he (and his friends) didn't know how to measure them correctly!

More Thanks

- Walt Maxwell, W2DU, for his great writing, and for his kind words.
- Danny, K6MHE, for prodding me to participate in a measurement roundtable that confirmed my work
- Henry Ott, WA2IRQ, for his insights, criticism, advice, and great teaching.
- Ron Steinberg, K9IKZ, for lots of help at critical times.
- The NCCC crew, for lots of antenna help.

Thanks to Richard Heyser

Dick's "day job" was at JPL, where he worked on underwater communications and communications for the space program, but audio was his hobby.

Dick invented Time Delay Spectrometry (TDS), which revolutionized audio by revolutionizing acoustic measurements. He was an articulate writer and teacher, teaching us how to always think about what we were measuring, to always question both the accuracy and the meaning of the data on the screen, and to use new ways of looking at the data to learn more from it.

References

- **Henry Ott, *Noise Reduction Techniques in Electronic Systems,* Wiley Interscience, 1988**
- **E. C. Snelling, *Soft Ferrites, Properties and Applications,* CRC Press, 1969**
- **E. C. Snelling and A. D. Giles, *Ferrites for Inductors and Transformers,* Research Study Press, 1983**
- ***Fair-Rite Products Catalog* This 200-page catalog is a wealth of product data and applications guidance on practical ferrites. http://www.fair-rite.com**
- ***Ferroxcube Catalog and Applications Notes* More online from another great manufacturer of ferrites. http://www.ferroxcube.com**

References

- ***New Understandings of the Use of Ferrites in the Prevention and Suppression of RF Interference to Audio Systems*** , **J. Brown** (AES Preprint 6564)
- ***Understanding How Ferrites Can Prevent and Eliminate RF Interference to Audio Systems*****, J. Brown** Self-published tutorial (on my website)
- **A Ham's Guide to RFI, Ferrites, Baluns, and Audio Interfacing** Self-published tutorial (on my website)

Applications notes, tutorials, and my AES papers are on my website for free download
http://audiosystemsgroup.com/publish

Coaxial Transmitting Chokes

Jim Brown K9YC
Santa Cruz, CA

http://audiosystemsgroup.com