Baluns & Common Mode Chokes

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2 September 2017

Part 2

Topics – Part 2

- Tripole
- Risk of Installing a Balun
- How to Reduce Common Mode currents
- How to Build Current Baluns & Chokes
  - Transmission Line Transformers (TLT)
  - Examples of Current Chokes
  - Ferrite & Powdered Iron (Iron Powder) Suppliers

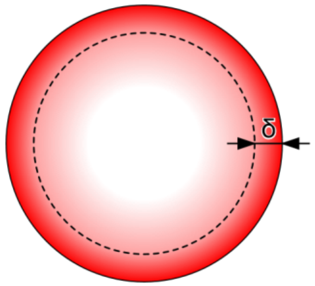
Sources of Common Mode Current

1. Balanced to Unbalanced signal mismatch
2. Asymmetry in antenna system
3. Pickup from external RF field

Tripole

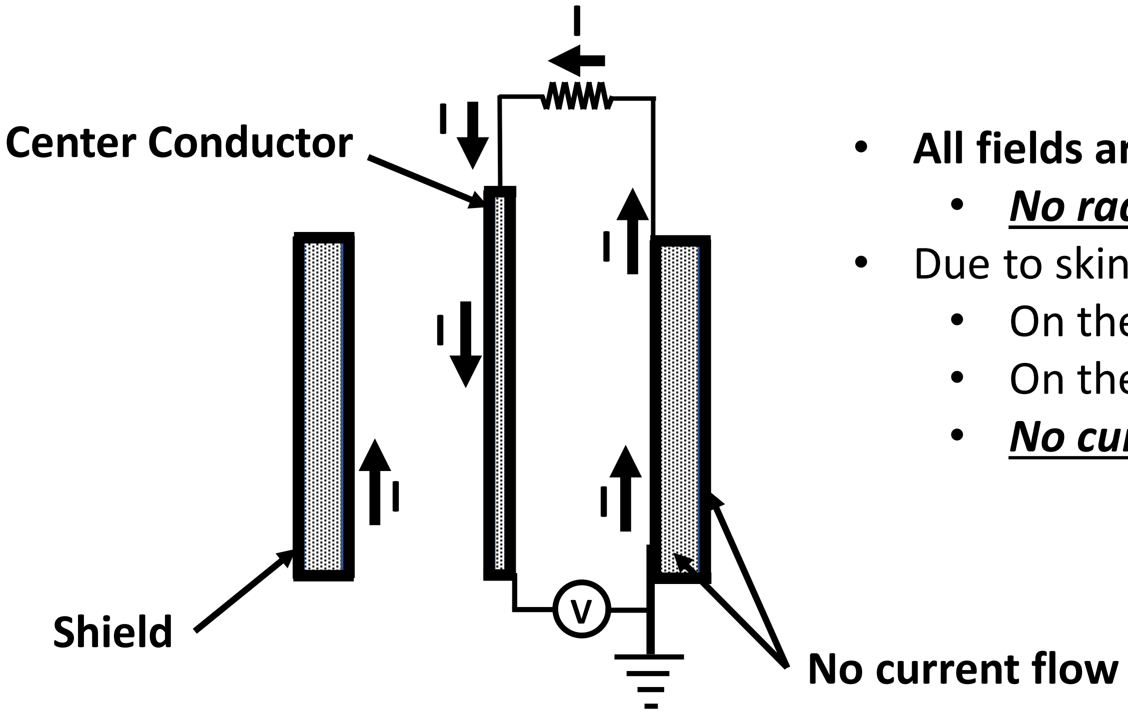
Skin Effect

- Skin effect:
  - RF currents flow near the outer surface of a conductor
  - The cause of Skin Effect is electromagnetic induction
    - Can be explained by Maxwell's equations
  - Skin depth = δ
    - The higher the frequency, the smaller the skin depth
  - Example (copper):
    - At 14 MHz skin depth = 0.7 microinch
    - Typical coax shield = 20 microinch



$$\delta = \sqrt{\frac{\rho}{\pi \times f \times \mu}}$$

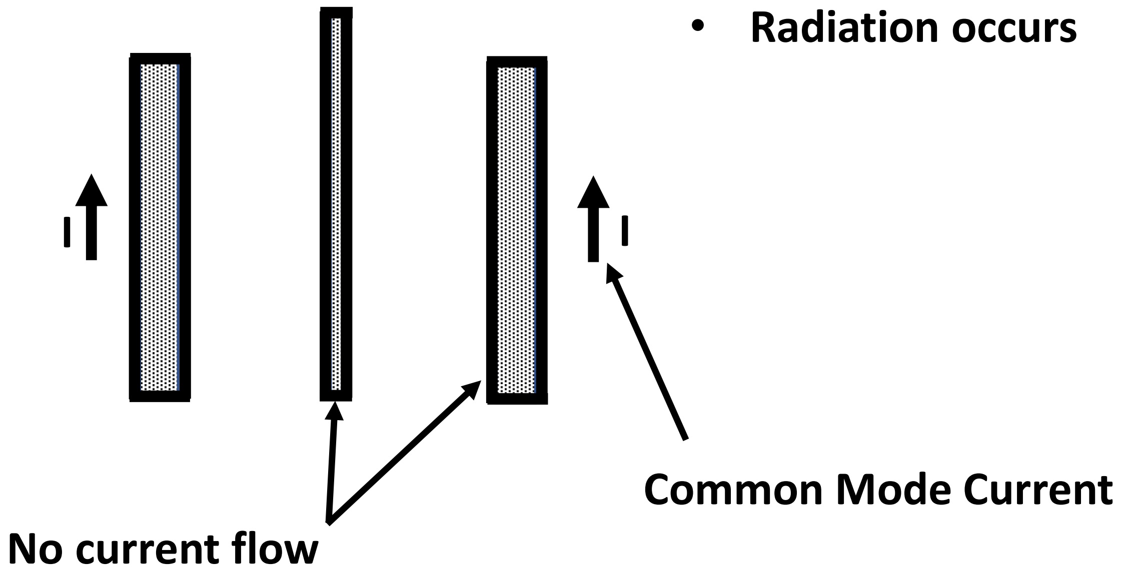
Differential RF Current Flow In A Coaxial Cable



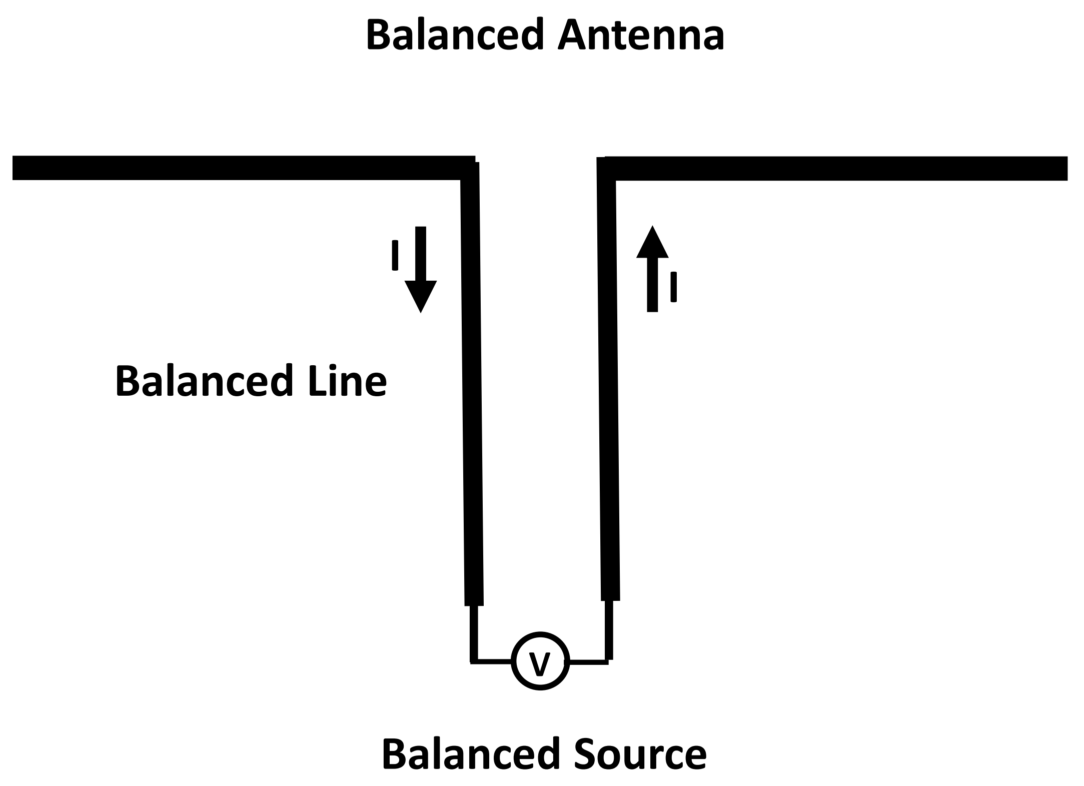
- **All fields are contained between the shield and the center conductor**
  - ***No radiation*** outside of an ideal cable
- Due to skin effect, Differential RF current flows:
  - On the outside of the center conductor, and
  - On the inside of the shield
  - ***No current on the outside of the shield***

Common Mode RF Current Flow In A Coaxial Cable

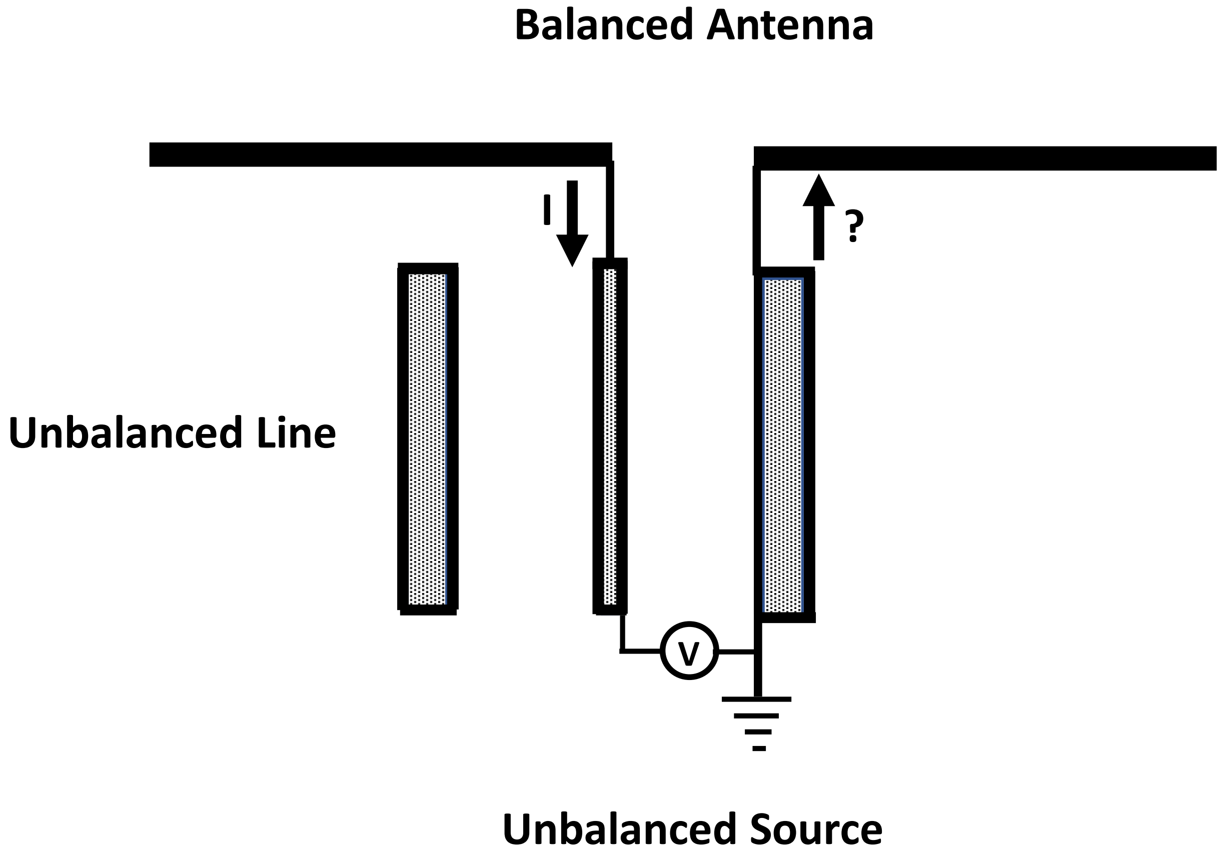
- Common Mode RF current flows on the ***<u>outside</u>*** of the shield
- **Radiation occurs**



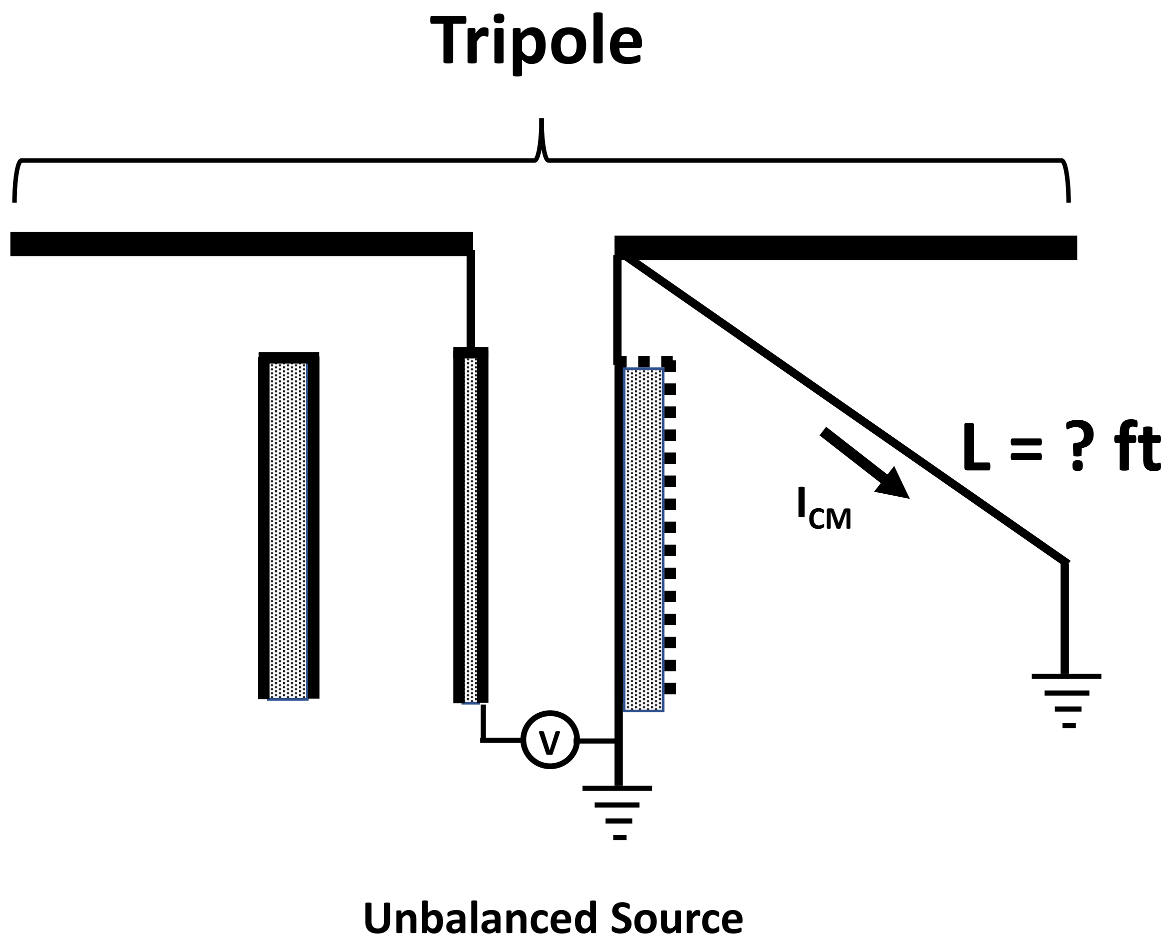
Balanced Dipole Fed With Balanced Line



Dipole Fed With Coax Without Balun

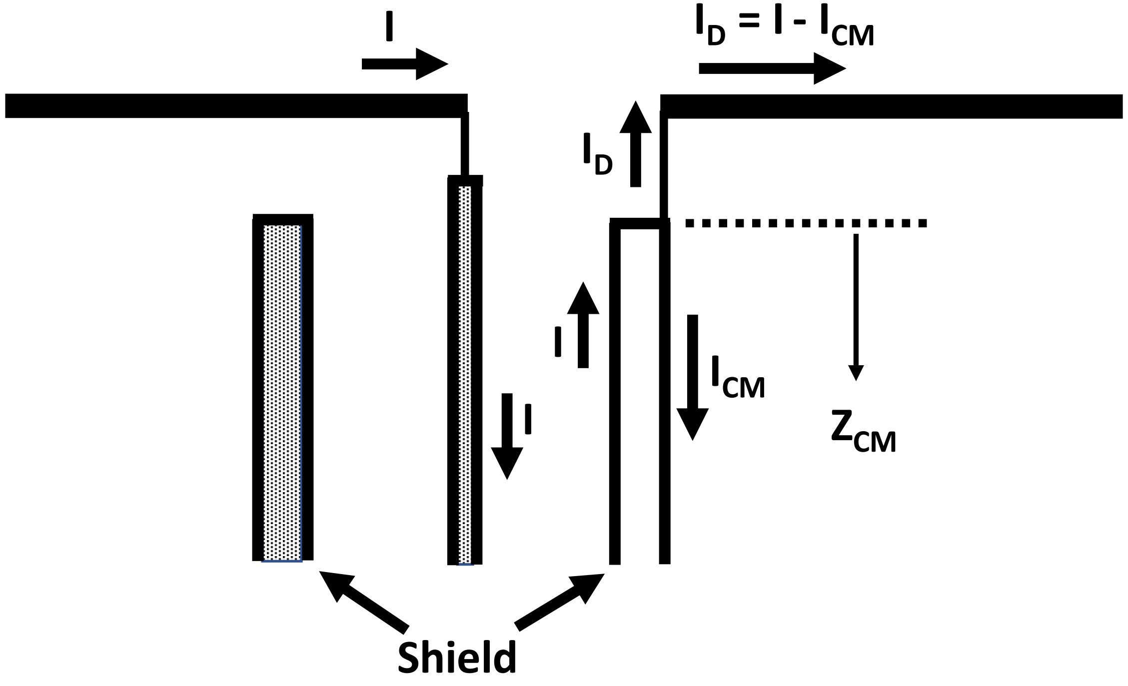


Dipole Fed With Coax Without Balun – cont'd



What Is a Tripole?

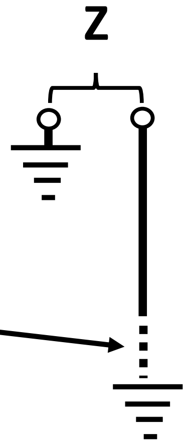
- A coaxial cable connected directly to a half wave dipole = “Tripole”

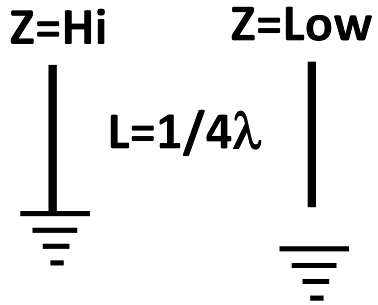


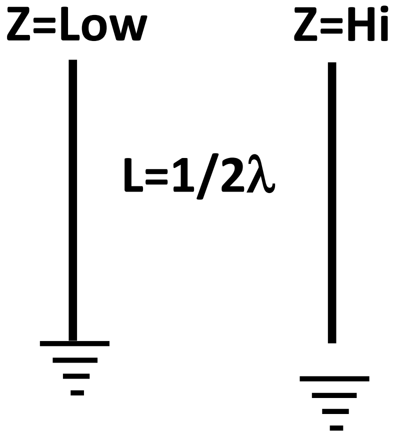
- Due to skin effect:
  - **Differential RF current:**
    - Flows only :
      - On the outside of the center conductor
      - On the inside of the shield
    - Sees three conductors when it reaches the dipole
      1) Left dipole element
      2) Right dipole element
      3) <u>Outside</u> of the shield
    - Current splits into I_D & I_{CM}
- The Common Mode Impedance of the shield = $\mathbf{Z_{CM}}$
  - $\mathbf{Z_{CM}}$ is a function of:
    - Frequency
    - Length of the coaxial cable
    - How the cable is terminated at the transmitter
    - Location of RF ground
    - RF characteristics of the ground

RF Impedance of a Conductor

- RF impedance of a short wire conductor is usually inductance + resistance
  - Short is < 1/10 wavelength
- RF impedance of a long wire conductor is a function of:
  - Frequency
  - Size
  - Length
  - Termination impedance
- $1/4\lambda$ inverts Z
  - $1/4\lambda$ vertical antenna => Z = 32 ohms
- $1/2\lambda$ replicates Z
  - End fed $1/2\lambda$ antenna => Z > 2000 ohms

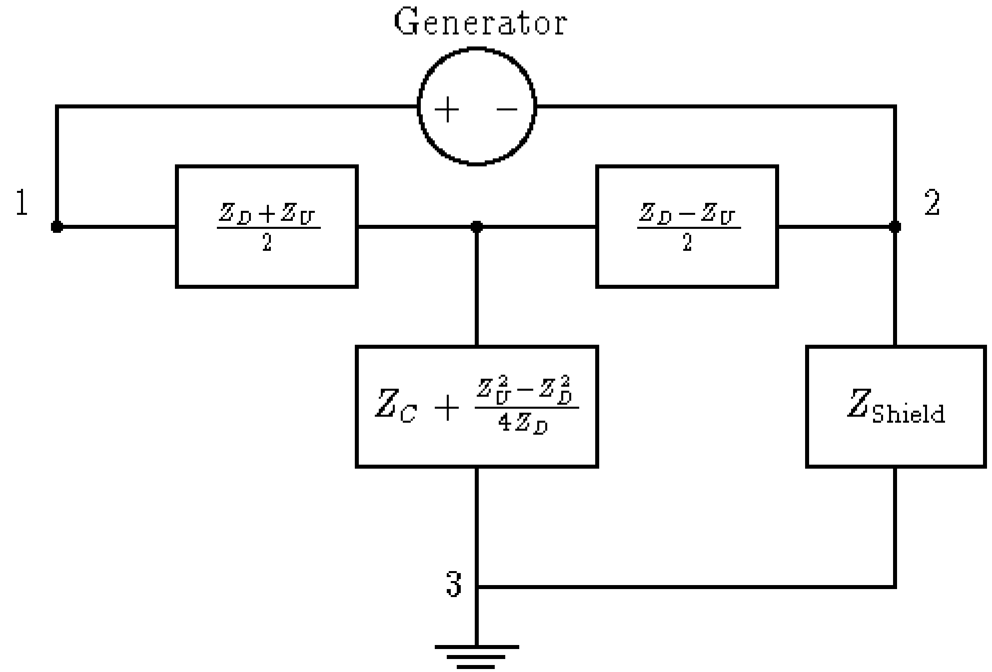




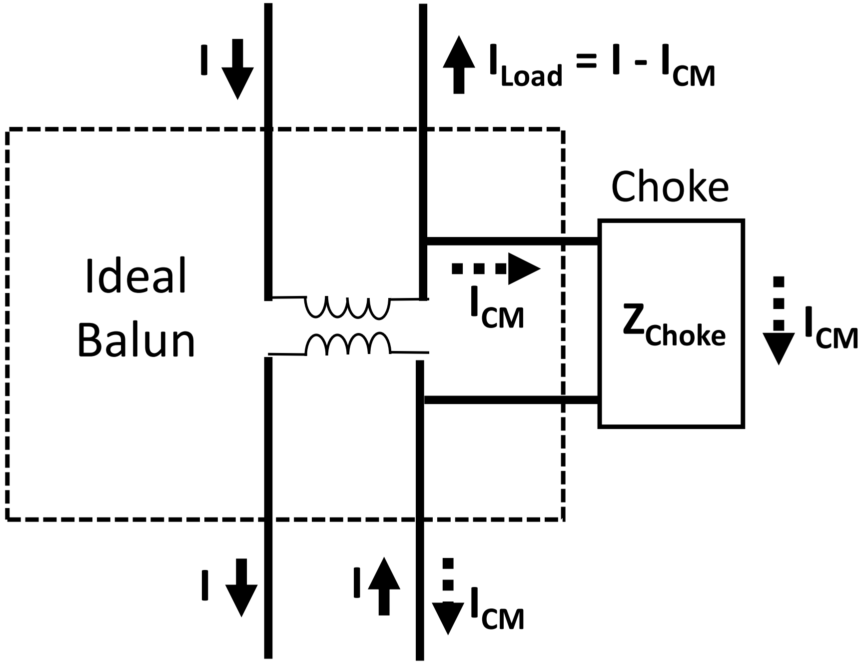


Circuit Models for Balun/Choke

Circuit model for Balun and Coax Shield



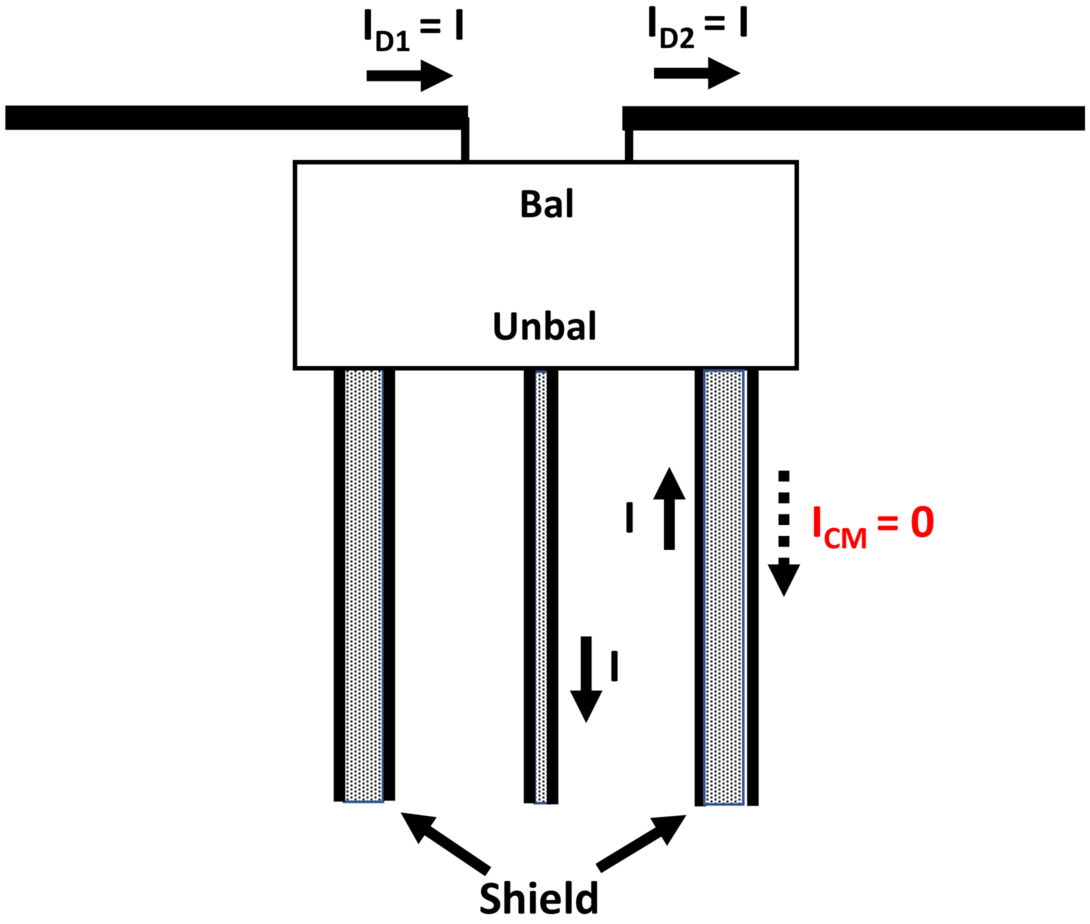
Simplified circuit model for Balun



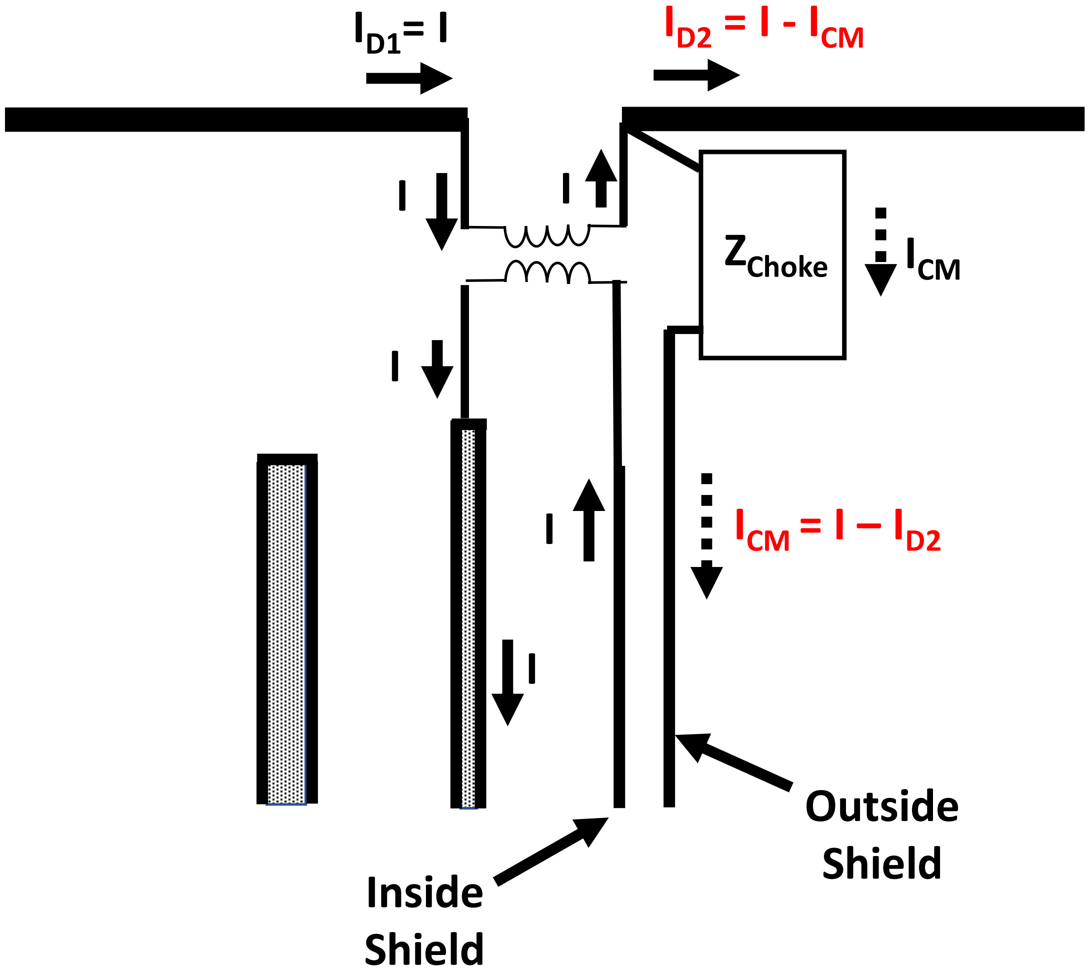
$$Z_{Choke} = R_{Choke} + jX_{Choke}$$

Dipole With a Balun

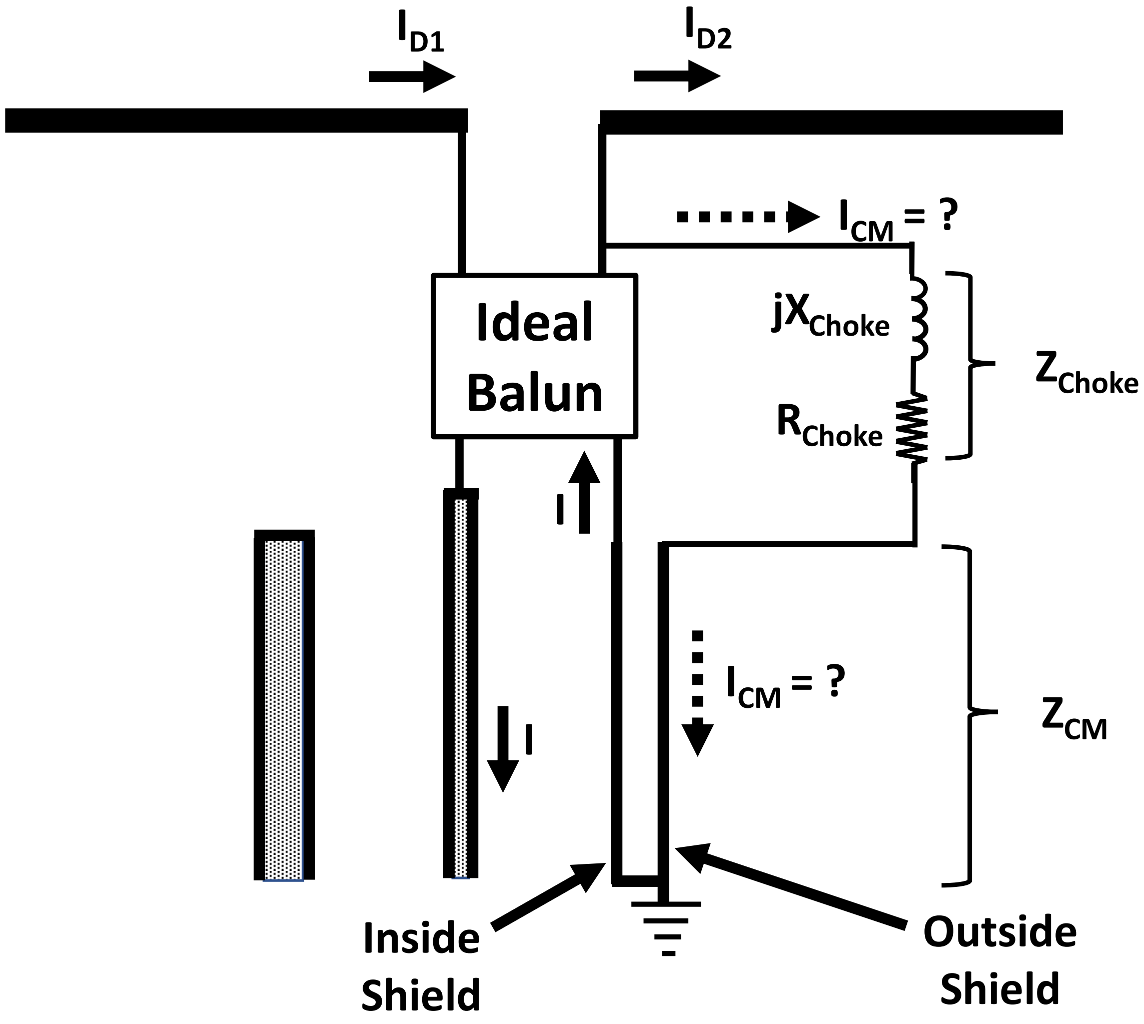
Ideal Balun



Real Balun

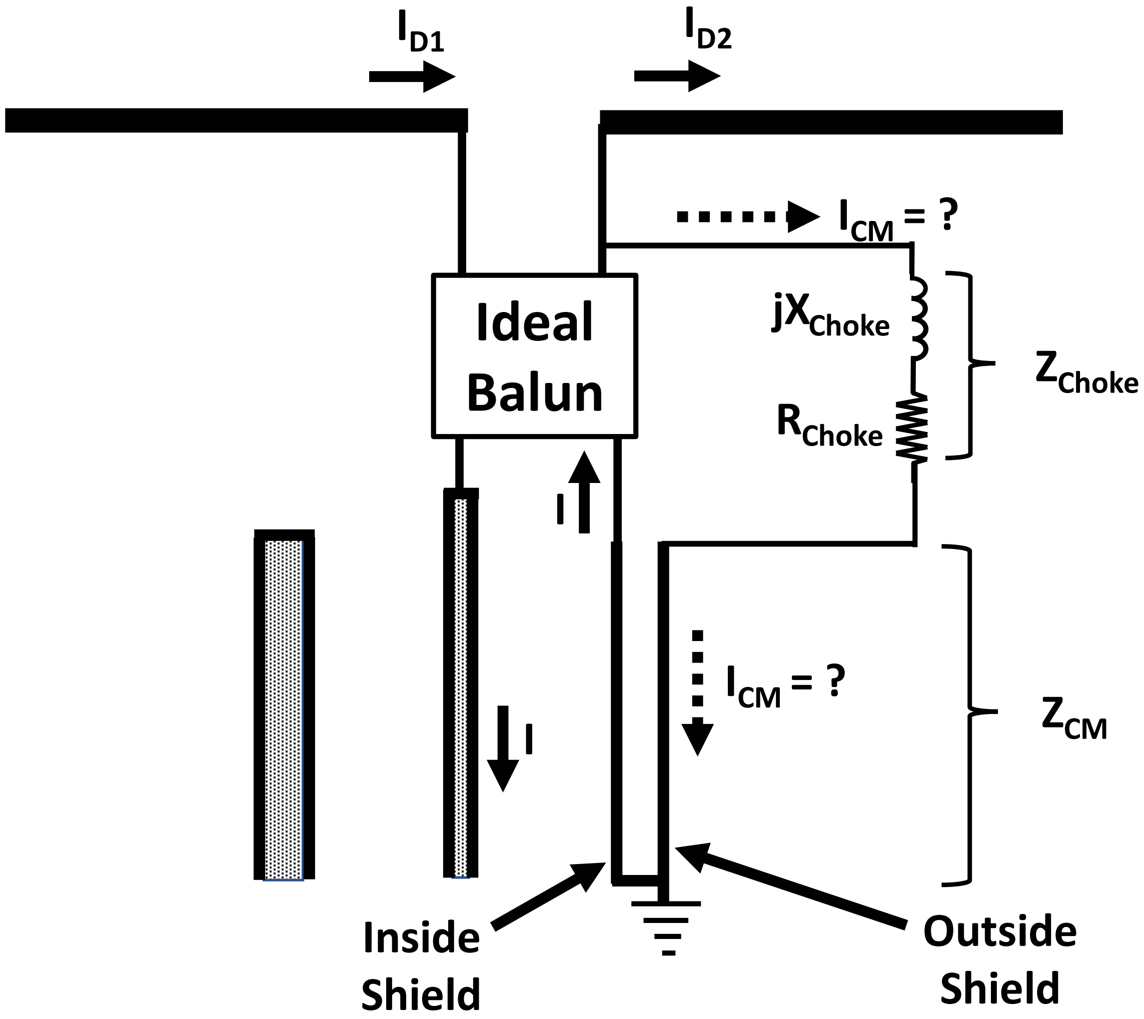


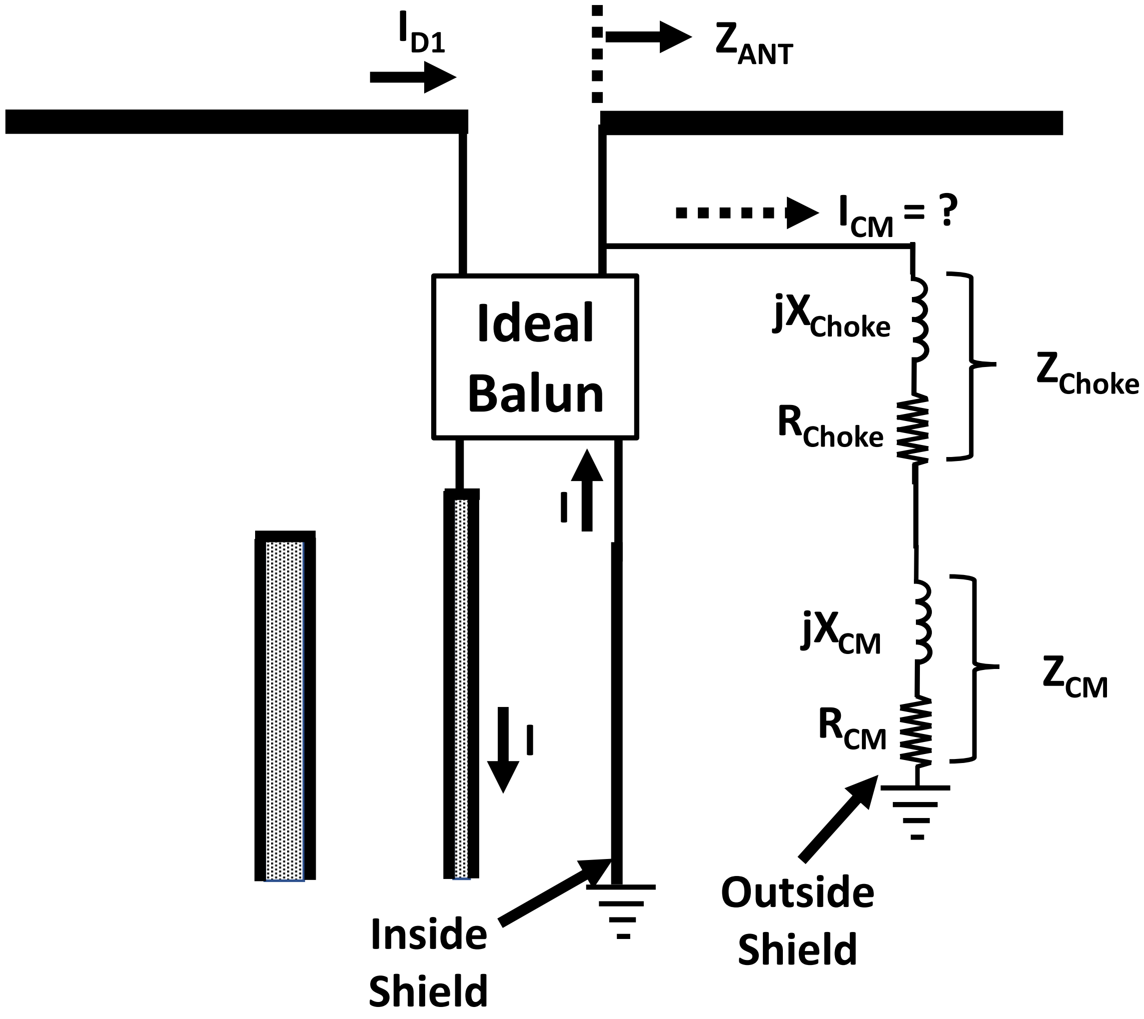
Dipole With Real Balun – cont’d



Only recently has the importance of Z_{CM} been understood.

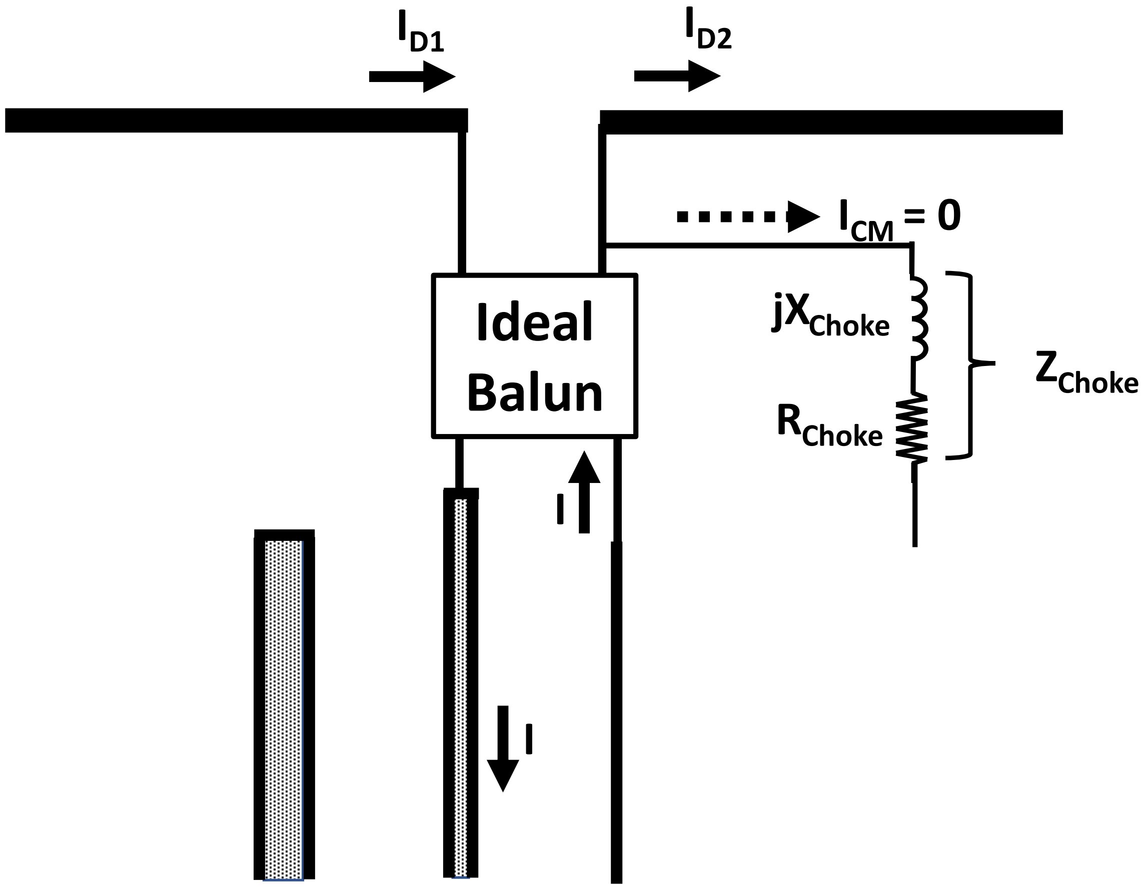
Dipole With Real Balun – cont'd



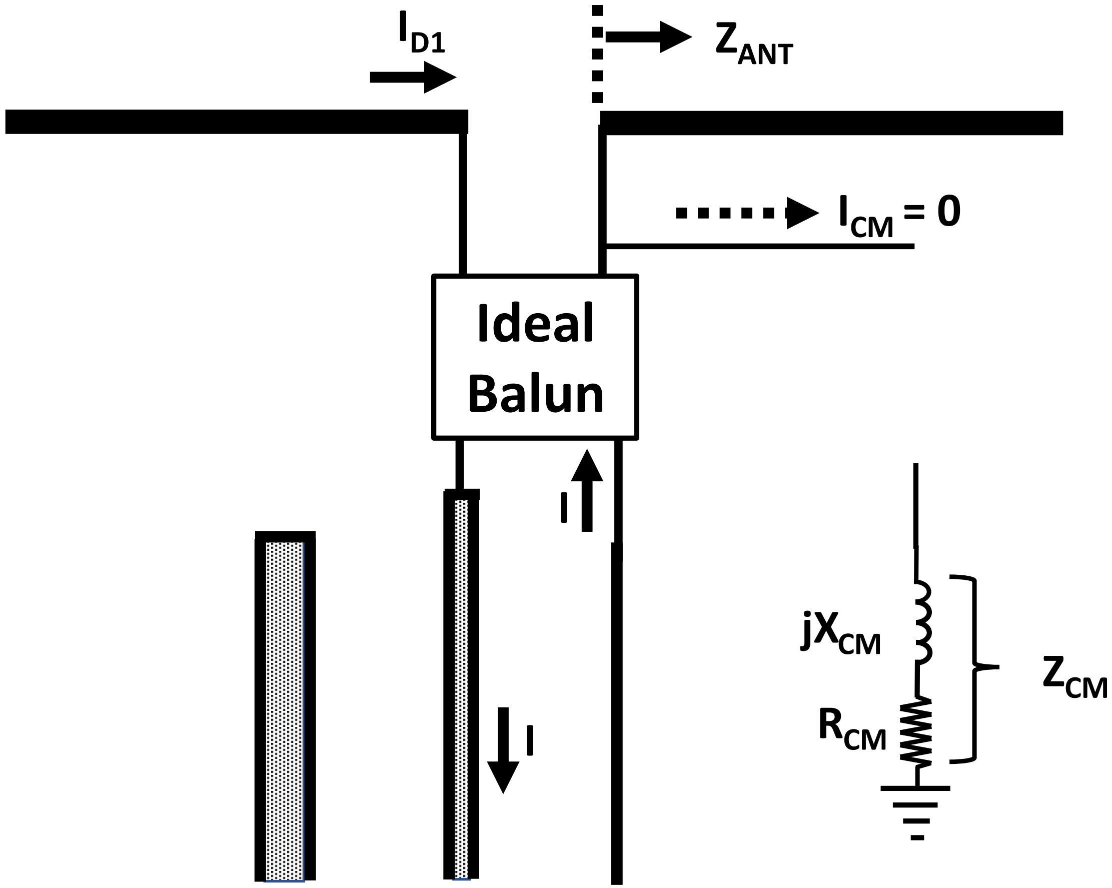


Dipole With a Balun – Two Ideal Cases

High Z_{CM}



High Z_{CHOKE}



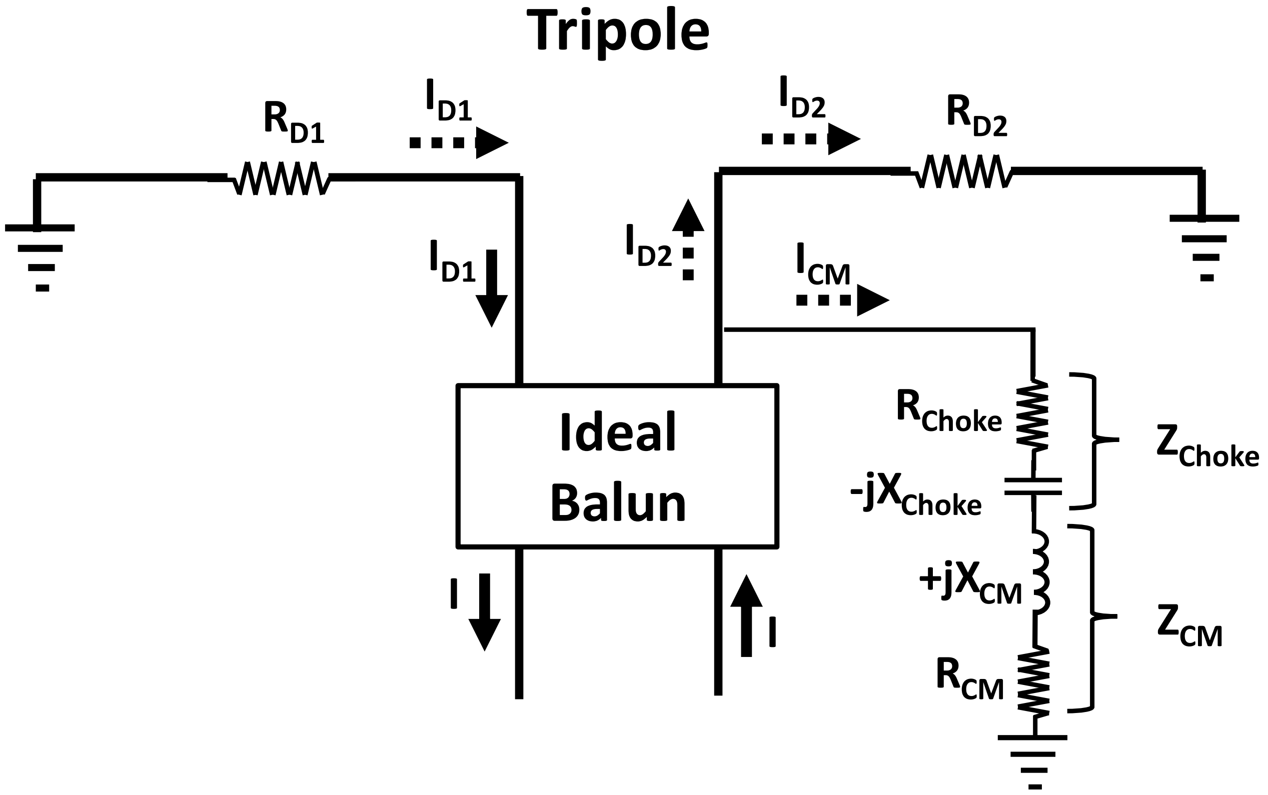
Risk of Installing a Balun

Risks of Installing a Balun

1. If you don’t have a Common Mode Current problem, installing a Balun may create one, or make an existing one worse
    - Common Mode current problems can be hard to identify
2. Failure of the Balun due to overheating
3. Increased InterModulation Distortion (IMD) on transmit signal

Unwanted *System* Resonance

- Resonance occurs when X_{CM} cancels X_{Choke}
  - I_{CM} is limited only by R_{CM} + R_{Choke}



When:

$X_{Choke} = -X_{CM}$ **and**

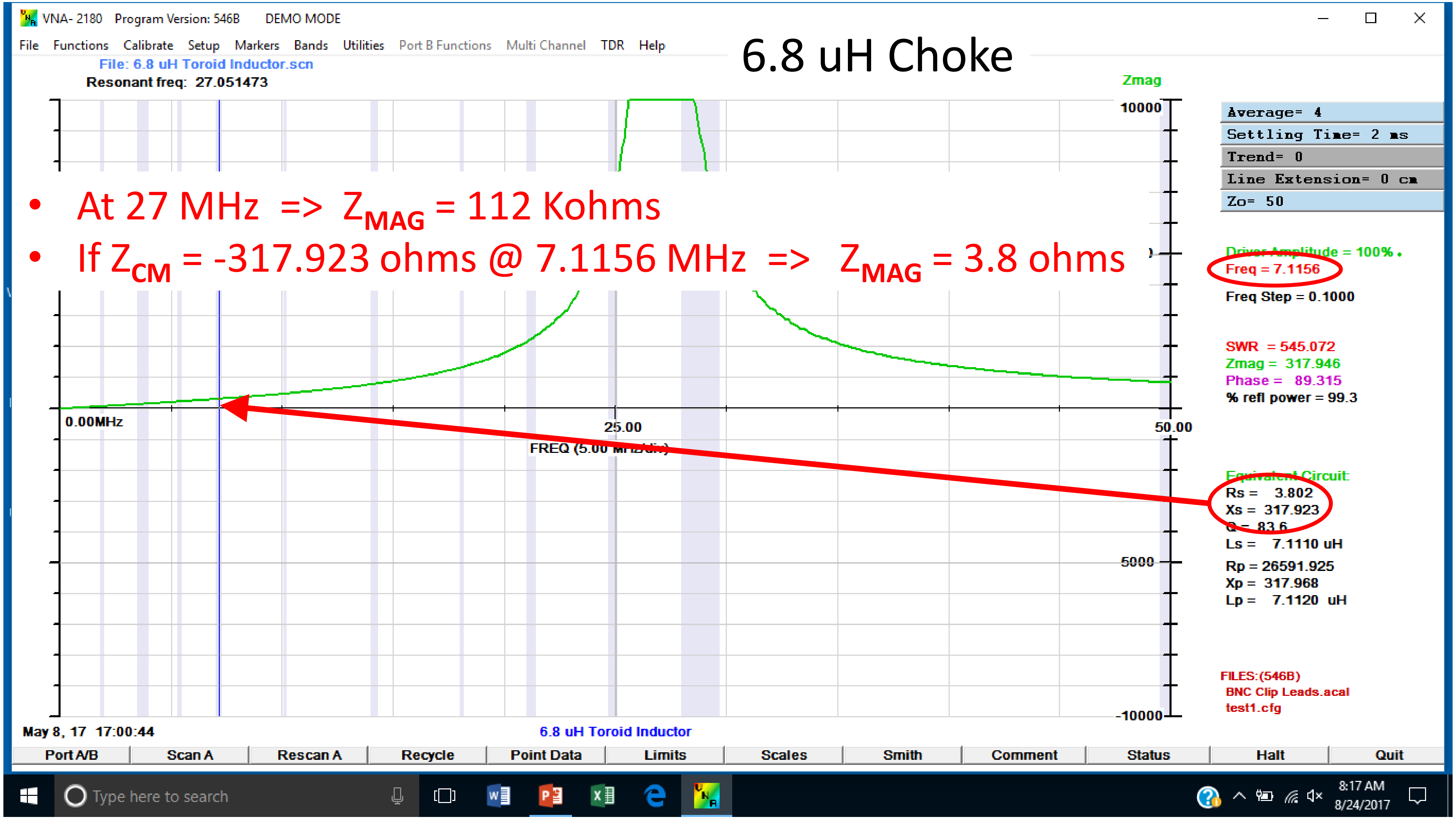
$(R_{Choke} + R_{CM}) << R_{D2}$

$I_{CM} = I$ **and**

$I_{D2} = 0$

Unwanted *System* Resonance – cont'd

- At 27 MHz => Z_{MAG} = 112 Kohms
- If Z_{CM} = -317.923 ohms @ 7.1156 MHz => Z_{MAG} = 3.8 ohms

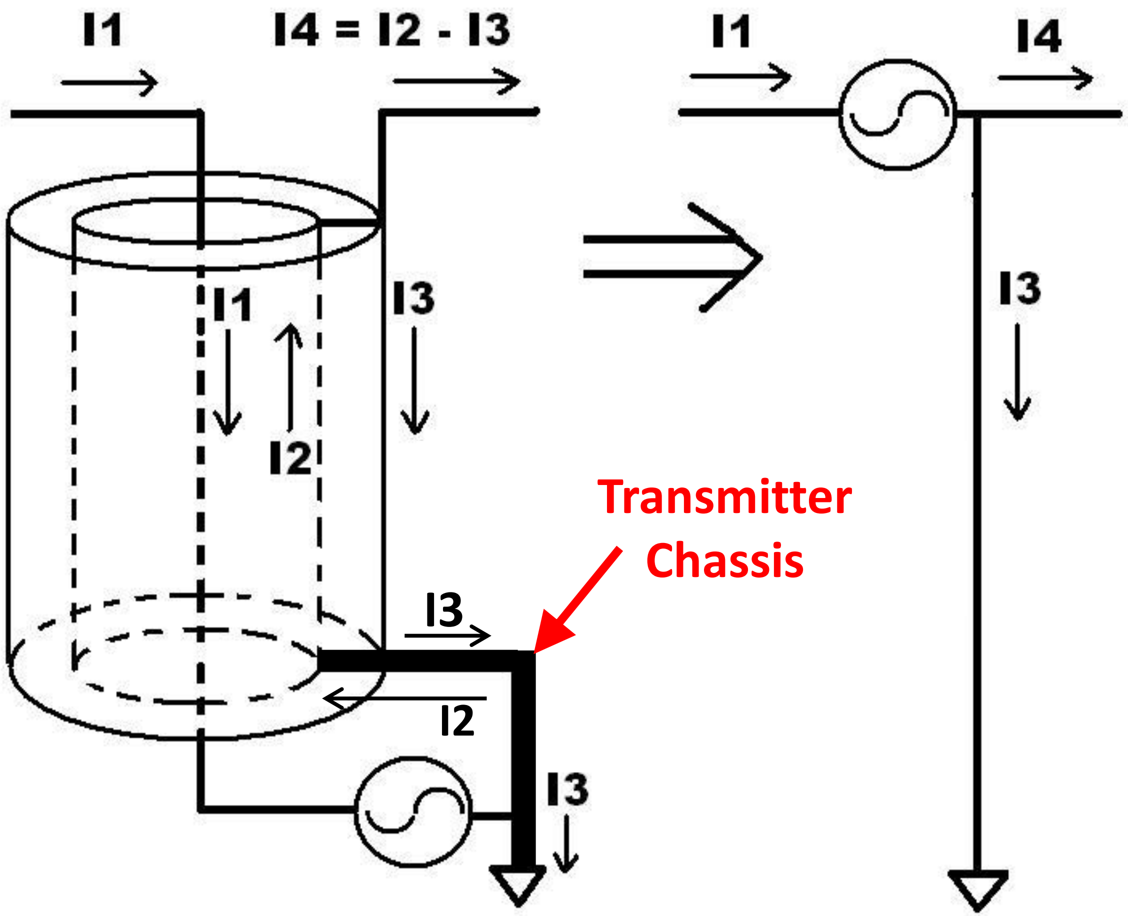


Common Mode Impedance of a Coaxial Cable Shield

- Z_{CM} is:
  - Very dependent upon:
    - Length and size of the cable
    - Location and impedance of the ***RF*** ground
  - Not easily measured
- ***EZNEC cannot model Common Mode Currents on a transmission line***

To Use EZNEC To *Roughly* Estimate I_{CM}: Tom Thompson (W0IVJ)

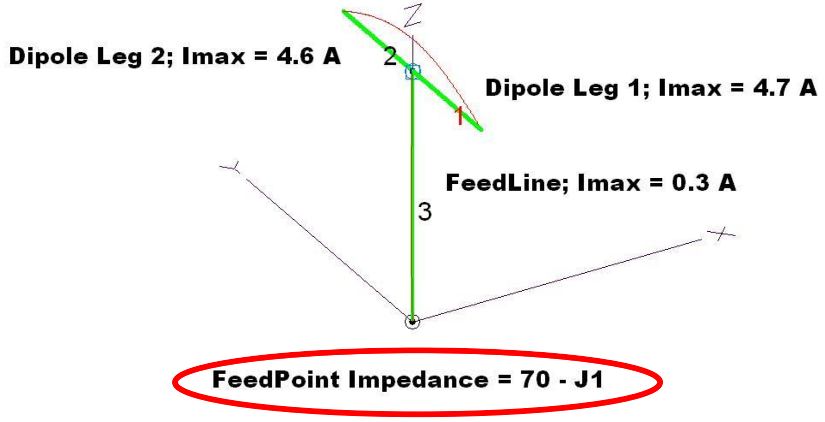
- Important assumptions:
  1. Perfect ***RF*** ground
  2. ***RF*** ground at known location
  3. No Balun
  4. Source moved up to antenna feed point
  5. Transmission line replaced with a wire



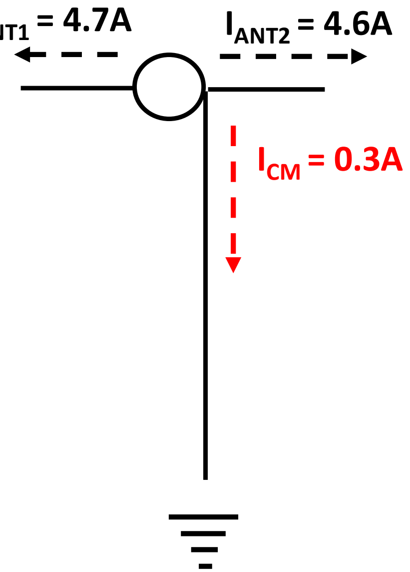
Example of Tripole Common Mode Current: Tom Thompson (W0IVJ)

- 40 M halfwave Dipole with **halfwave wire for feed line**
- No Balun
- Tx power = 1500 W
- Feedline **<u>NOT</u> grounded**

This is a dipole!

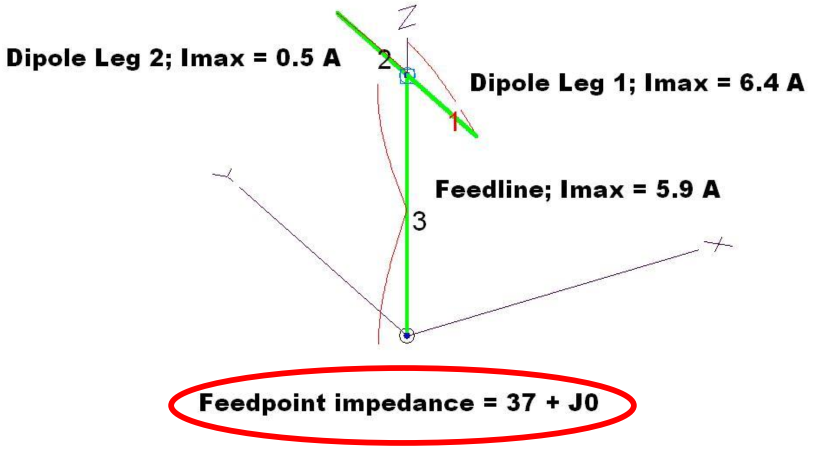


40 meter dipole with ~1/2 wl feedline ~1/2 wl above perfect ground. Feedline is NOT grounded.

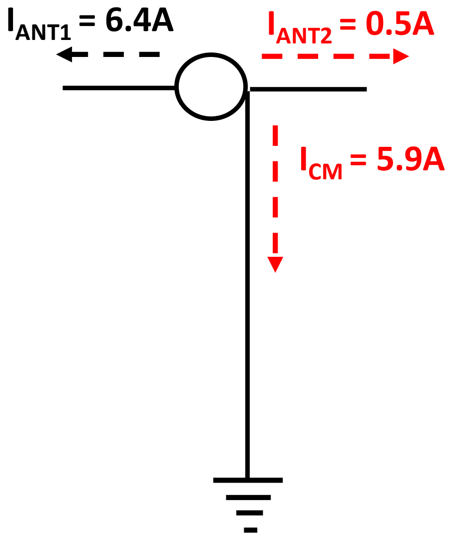


Example of Tripole Common Mode Current - cont'd

- 40 M halfwave Dipole with **halfwave wire for feed line**
- No Balun
- Tx power = 1500 W
- Feedline **grounded**



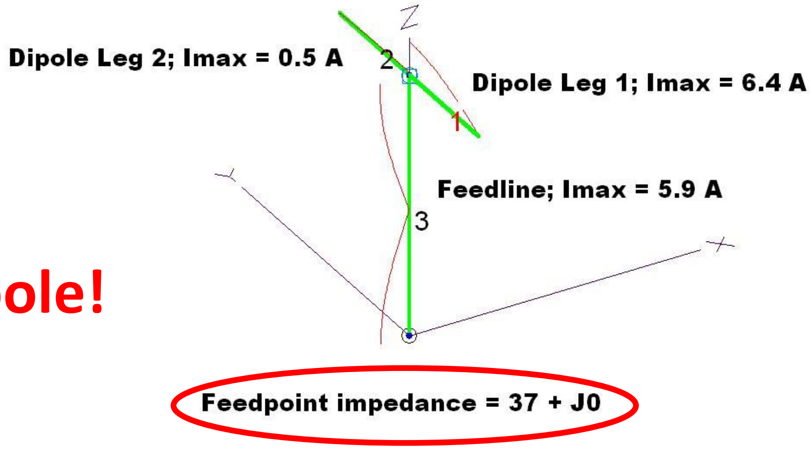
40 meter dipole with ~1/2 wl feedline ~1/2 wl above perfect ground. Feedline IS grounded at transmitter end.

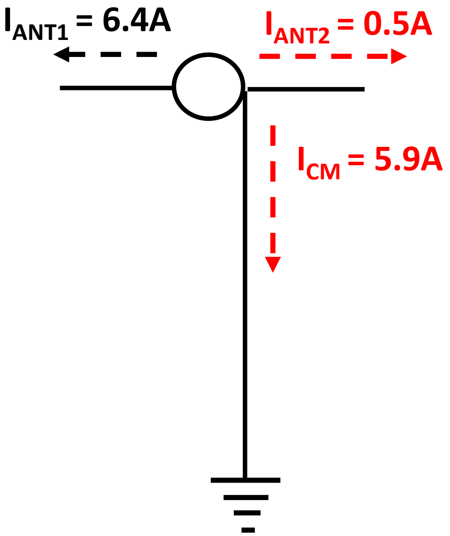


Example of Tripole Common Mode Current - cont'd

- 40 M halfwave Dipole with **halfwave wire for feed line**
- No Balun
- Tx power = 1500 W
- Feedline **grounded**

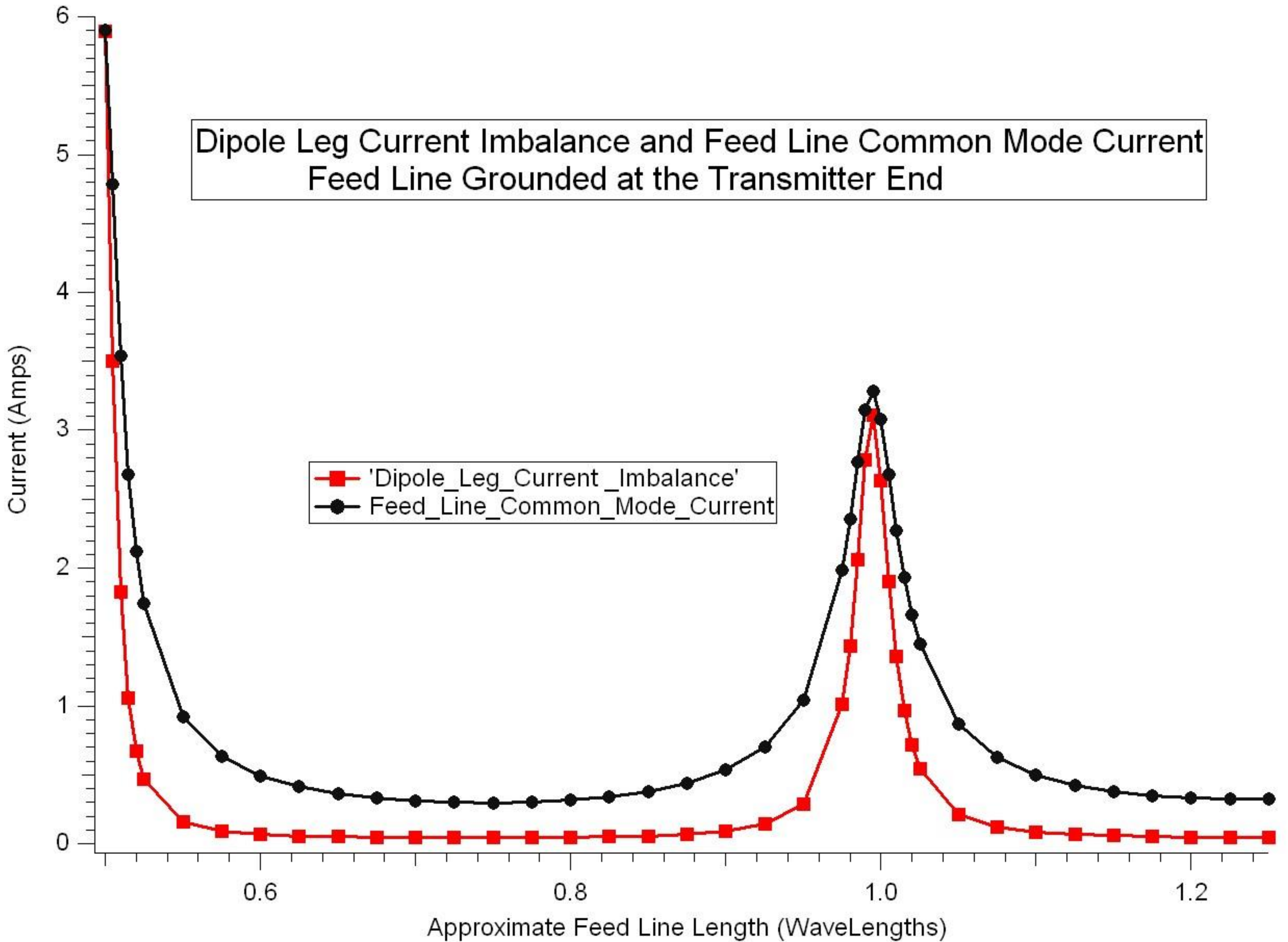
This is an inverted L antenna, not a dipole!





40 meter dipole with ~1/2 wl feedline ~1/2 wl above perfect ground. Feedline IS grounded at transmitter end.

Importance of Transmission Line Length : Tom Thompson (W0IVJ)



Importance of Transmission Line Length – cont'd

- How long should a transmission line be to minimize I_{CM} ?
  - Note: length is physical length (x 0.98) to **RF** ground
  - **No Balun**:
    - Monoband antennas:
      - Use odd multiple of ¼ wavelength
    - Multiband antennas: There may be no one length that is good for all bands
  - **With Balun**: ???
    - Chose a length that will avoid resonance
    - Some "Experts" recommend multiple of ½ wavelength
      - This seems like the worst choice to me => Use odd multiple of ¼ wavelength

Options When Installing a Balun

- Bottom line: it can be hard to predict what a Balun will do in any system
  - Option 1: Install a Balun/Choke and hope it is helping and not overheating
  - Option 2: Measure Common Mode Current with and without a Balun
    - Must measure current on outside of coax shield (not the Differential Current)

Roy Lewallen
W7EL
"Baluns: …"

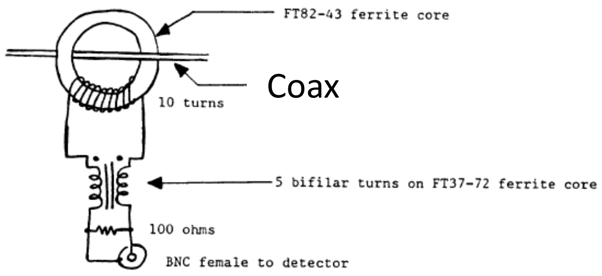


Fig. 12 — Current probe.

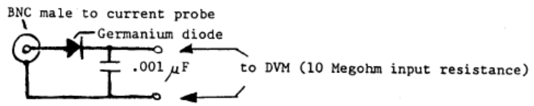
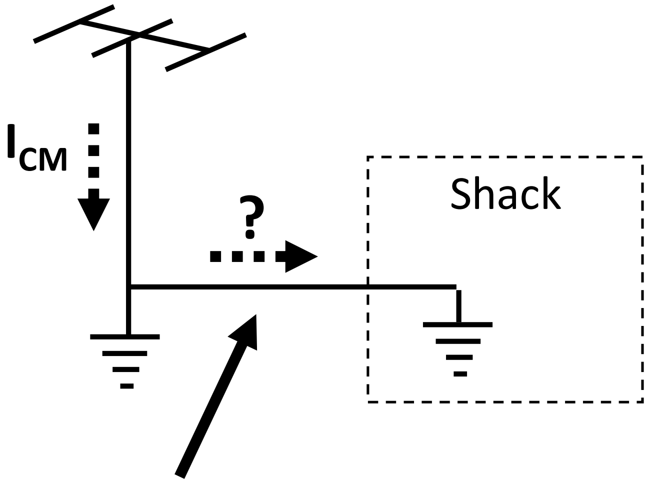
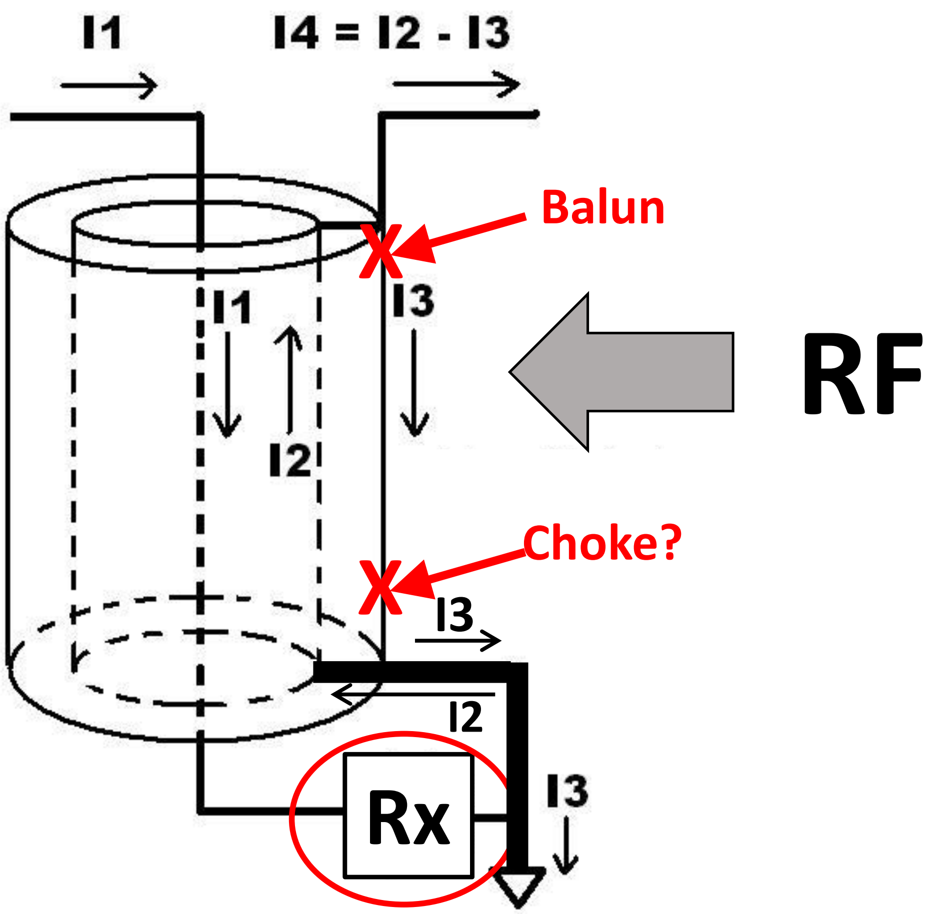


Fig. 13 — Detector.



    - Making the measurement inside the shack may give erroneous reading
  - Option 3: Monitor temperature rise of Balun/Choke during transmit
    - A choke may be cool because it isn't doing anything

Common Mode Currents Can Be Generated By External RF



- A Balun also reduces Common Mode current due to external RF fields
  - Some claim 1 to 5 S unit noise reduction
- Some claim that an additional Current Choke is required at the station to:
  - Reduce interference in the receiver => ??
    - **No documentation found showing when this is a problem**
  - Reduce Common Mode Currents caused by asymmetrical coupling to the line
    - **No documentation found showing when this is a problem**

Where Should Baluns/Chokes Be Placed

- Start with a Balun at the antenna
- A Common Mode Choke at the transmitter?
  - No analytical or empirical justification found
- Common Mode Chokes as “Egg Insulators” every ¼ wavelength?
  - No analytical or empirical justification found
- Use many chokes in series to increase net impedance (ie, CMMR)?
  - ***Point of diminishing returns***
    - Example: $Z_{\mathbf{Choke}}$ = 10,000 Kohm & $Z_{\mathbf{CM}}$ = 100 ohm

      CMMR

      - 1^{st} choke => 40 dB
      - 2^{nd} choke => 46 dB
      - 3rd choke => 50 dB

Overheating

- Two Sources with Transmission Line Transformers (TLTs):
  1. Coaxial Transmission Line loss
     - Power spec based upon open-air applications (not enclosed in a box)
     - Deformation (coiled & hot) => degraded performance => failure (high SWR or short)
       - Minimum bend radius
       - This is what balun mfg's power specs are based on
  2. Core loss
     - Voltage Balun: both Common Mode *and* Differential Mode currents heat the core
     - Current Balun: only the Common Mode current heats the core
     - Heating increases with increasing permeability (ie, core loss)
     - ***This power limit is never spec'd by mfgs and is usually the important limitation***
     - Two sources of overheating:
       - From resonance with a reactive choke
       - With a resistive choke with insufficient resistance

Overheating –cont’d

- Difficult to remove heat from a small enclosed box & and from ferrites
  - No air flow
  - No heat sinking options
  - Low thermal conductivity of ferrites & powdered iron

Power Dissipation – Jack Lau W1VT

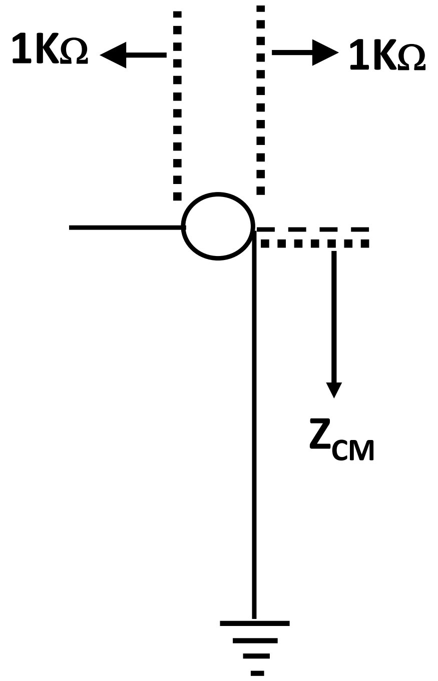
QEX_Jan_2004_p55-58.pdf - Adobe Reader

Worst Case Example: using an 80 M dipole on 20 M

Jan/Feb 2004 QEX:
Max Power Dissipation for 2” core ~ 4 Watts

A high-impedance antenna and a low-impedance path shield. The applied power is 1-kW at 14.0 MHz.

Balun Z_{CM}	*Shield Current* *(A)*	*Balun Loss* *(W)*	*(dB)*
1000 Ω	0.5	253	1.3
2000 Ω	0.3	211	1.0
4000 Ω	0.2	144	0.7
10000 Ω	0.08	72	0.3
20000 Ω	0.04	39	0.2
W2DU bead balun 1300 –*j*400	0.44	258	1.3
6t RG-213 4-1/4” dia 6 + *j*514	0.74	3	0.01
12t RG-213 4-1/4” dia 449 + *j*5833	0.14	9	0.04
12t RG-213 @7.00MHz 5 + *j*561	0.72	2.6	0.01
12t RG-213 @28.00MHz 30 –*j*482	1.34	54	0.2



Power Dissipation – Jack Lau W1VT

QEX_Jan_2004_p55-58.pdf - Adobe Reader

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Worst Case Example: using an 80 M dipole on 20 M

Note: Even well balanced antennas can have high Common Mode currents! This fact is missed by many "Experts".

1000 Ω	0.5	253	1.3
2000 Ω	0.3	211	1.0
4000 Ω	0.2	144	0.7
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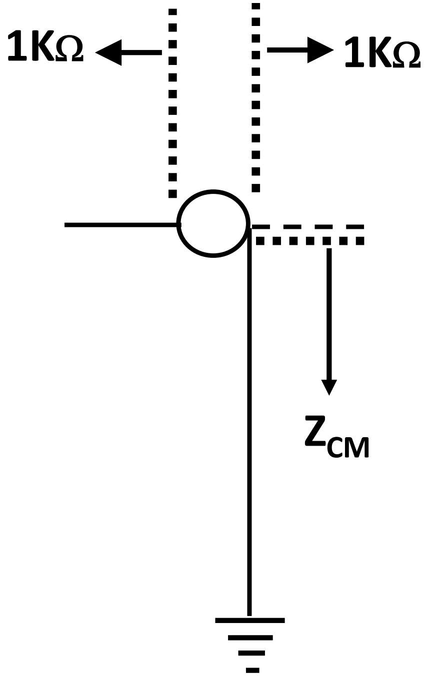

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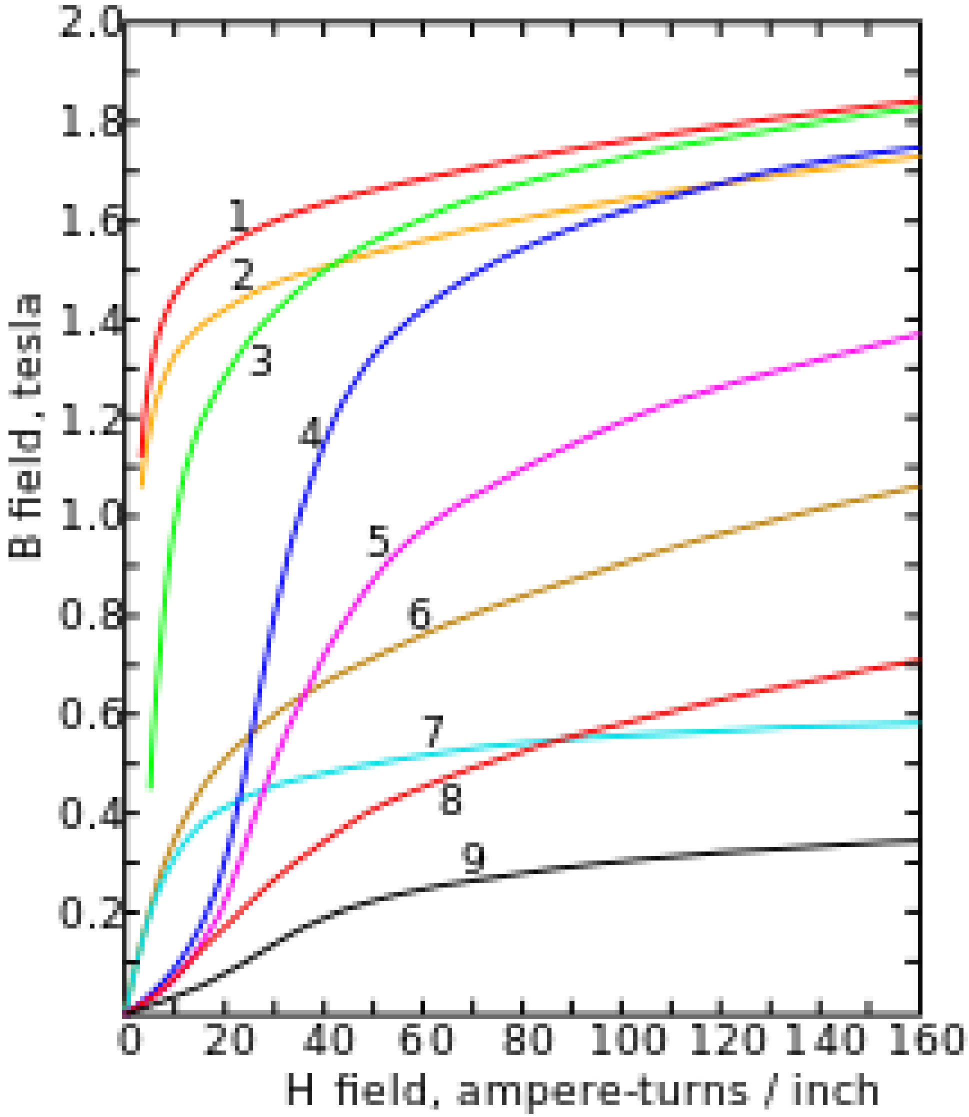
Intermodulation Distortion

- Ferrites are non-linear components
  - They can generate IMD just like an overdriven amplifier
  - Hard to know when this is occurring
- **Avoid operating near saturation!**
  - **Thermal run-away**



Building Current Baluns & Chokes

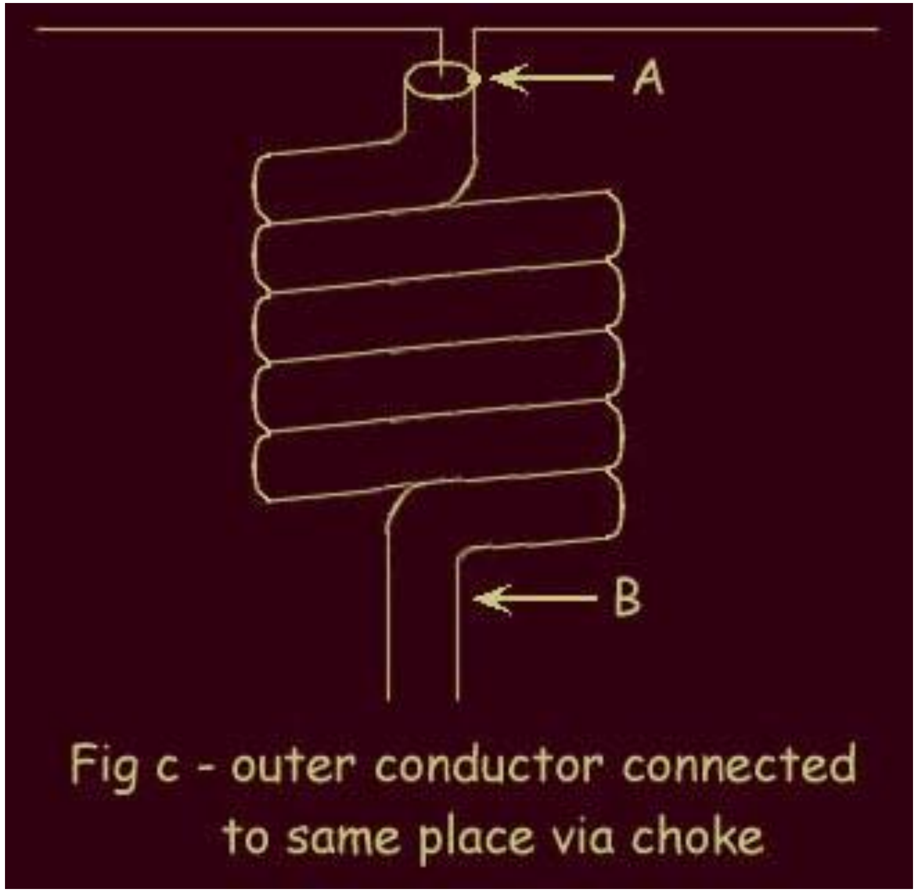
Types of Common Mode Current Chokes

- Inductively Coupled Air Core Coils
  - Rarely used today
- Powdered iron
- Ferrite
- Ferrite Sleeved Coax Baluns
- Coiled Coax “Ugly” Baluns
- Transmission Line Transformer (TLT) Baluns

Design Goals for Common Mode Current Chokes

- High Common Mode impedance
  - At least 500 ohms (>5 Kohms recommended)
  - Resistive vs Reactive?
    - Resistive is better is you can get the impedance high enough (ie, no overheating)
- Low Differential Mode SWR & loss
- Adequate power limits
  - Differential Mode (easy)
  - Common Mode (difficult design problem)
- Desired frequency range
- Optimized bandwidth
  - Wideband vs. narrowband
- Optimized SRF

How Common Mode Current Chokes Work

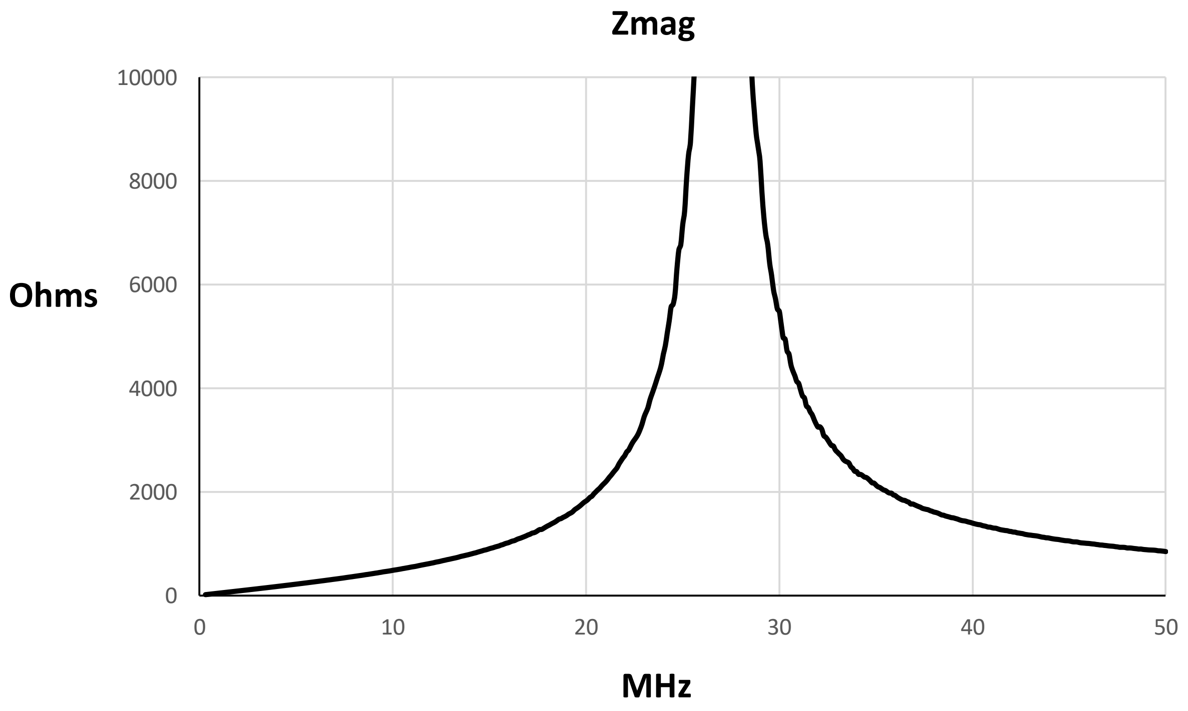


- Differential Mode signal only sees the coax
  - Coiling the coax has no effect
  - Typical:
    - SWR < 1.1:1
    - Loss < 0.1 dB
    - Bandwidth (depends on coax)
- Common Mode signal only sees the choke
- Common Mode impedance is a function of:
  - Number of turns
  - Coil dimensions
  - Frequency
  - Core media (ferrite, air, …)

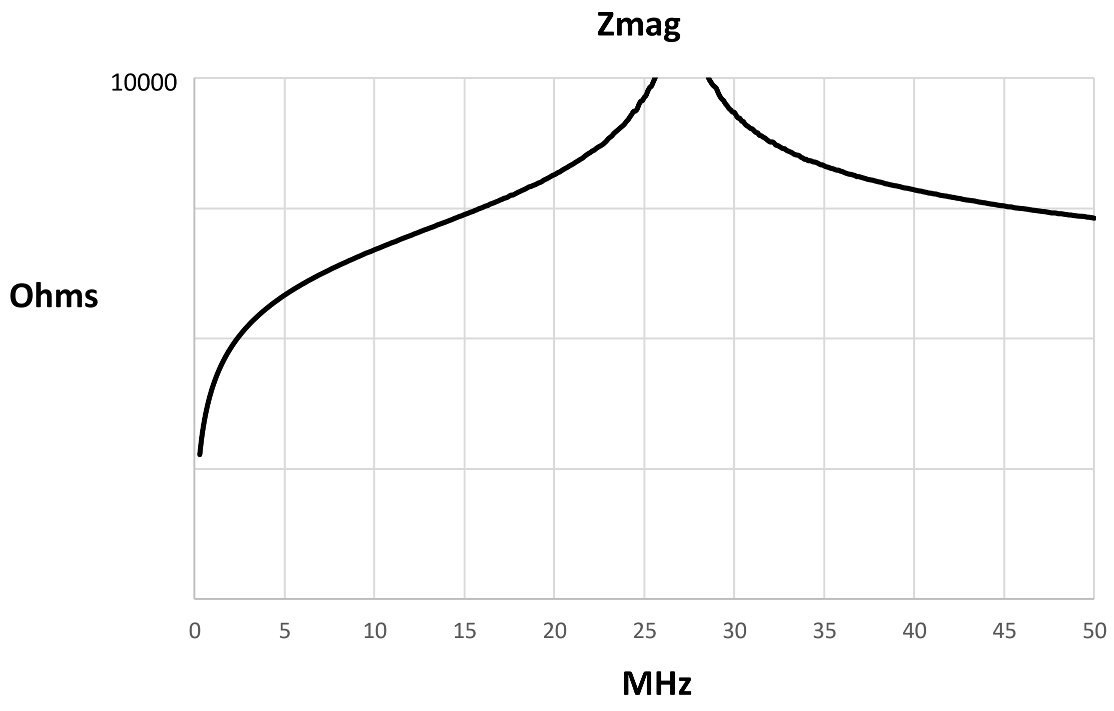
Choke Impedance Performance Claims

- ***Be careful!***
- Some charts of performance can be misleading

6.8 uH Choke #1



6.8 uH Choke #2

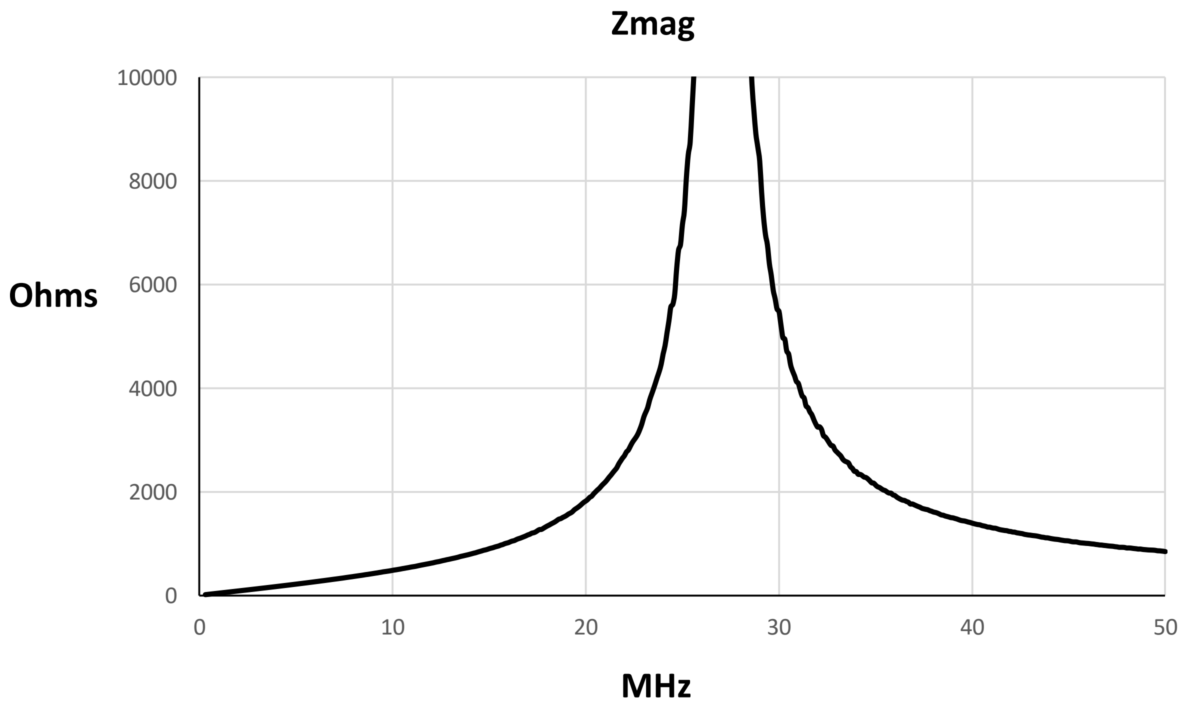


Choke Impedance Performance Claims

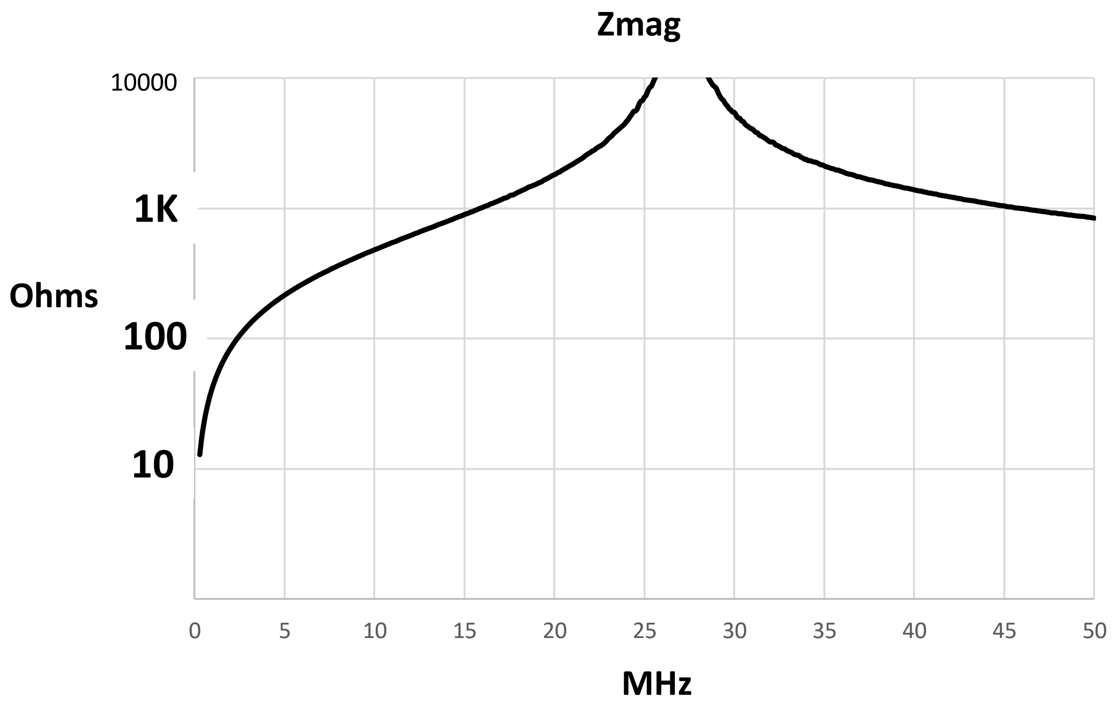
- Be careful
- Some Charts of performance can be misleading

Same 6.8 uH Choke

Linear



Log



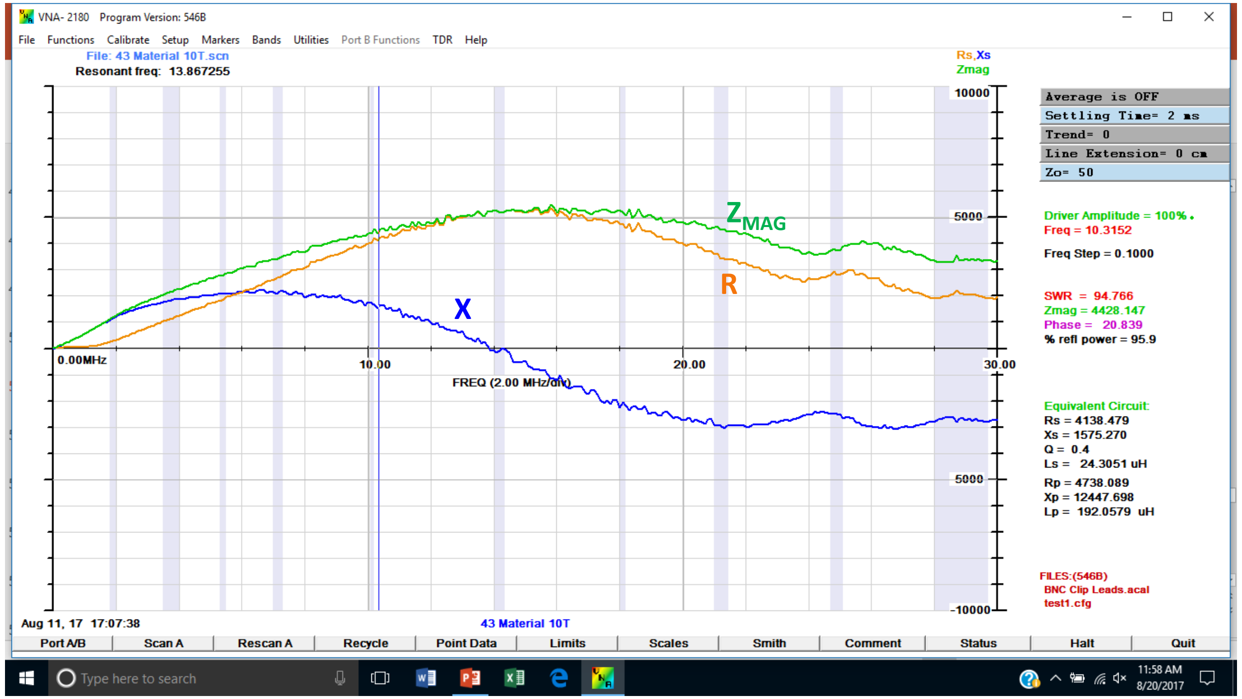
Powdered Iron

- Low permeability = u = how much inductance per turn)
  - Very low loss (ie, hi Q = narrowband)
    - Less heating of the core
    - Impedance is mostly inductive reactance
  - Very low Z/turn
- Rarely used for Baluns/Chokes
  - Commonly used for high Q inductors
- Example:
  - To get ~20 uH on T50-6 (u=8) requires ~50 turns
    - No way to get this many turns of coax around even the largest core available
    - Ferrite cores would only require 4-6 turns
  - Impedance at 10 MHz:
    - Resistance: only 45 ohms
    - Inductive reactance: 1300 ohms

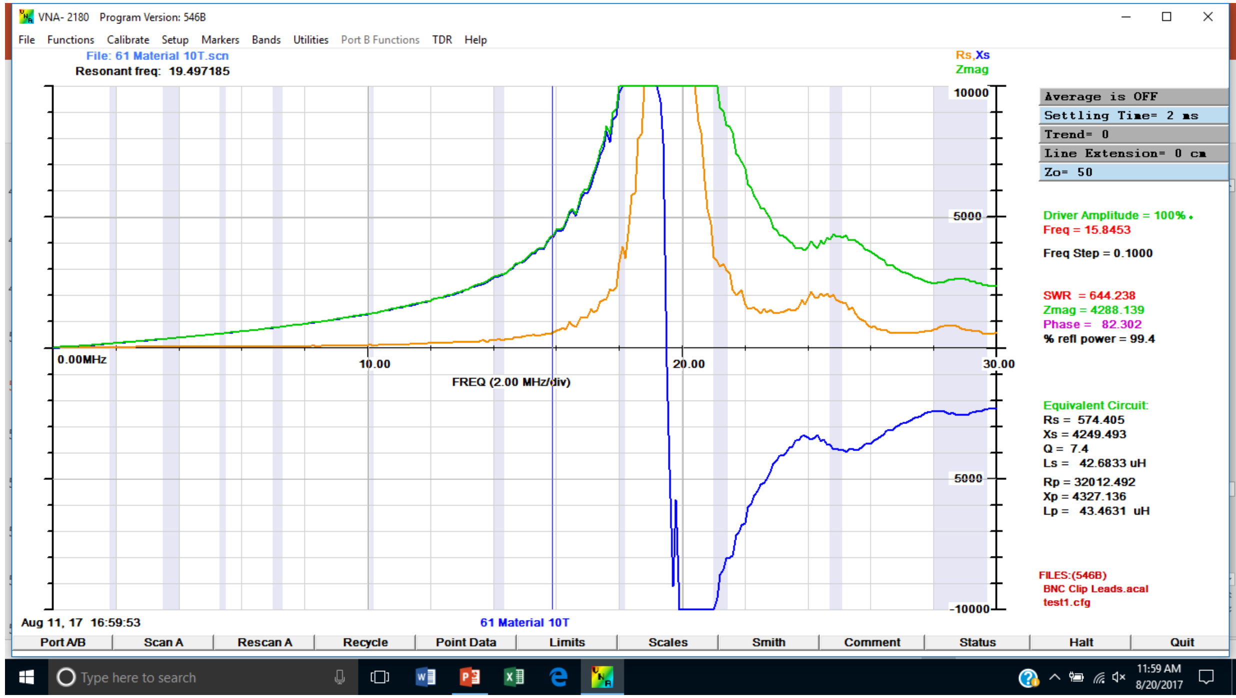
Ferrites

- Wide range of permeability (u)
  - Mix:
    - “31”: u=1500 “33”: u=600 “43”: u=800 “61”: u=125 “77”: u=2000
- Impedance examples (10 turns around a 2.4 inch core):

Type 43



Type 61



Ferrite Sleeved Current Chokes

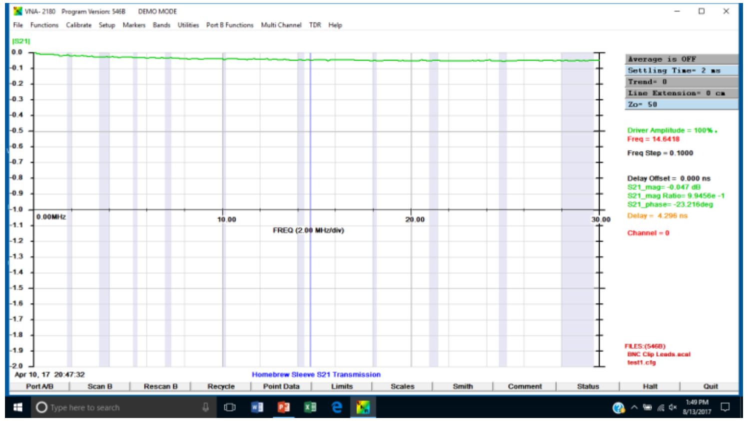
- Ferrite beads over coax
  - These chokes are 1:1 UNUNs
- Mostly resistive impedance
  - No system resonance risk
  - Low Q (wideband)
  - Difficult to achieve sufficient choking impedance
    - No n^2 multiplier as with coils
    - May need to use more than 100 beads
  - **History of failures from overheating**
    - “W2DU design overheats at 500W”
- Simple to build but not necessarily cheap
  - Comtek uses 100 beads ($130)

Ferrite Sleeved Current Chokes – cont'd

- Homebrew Sleeved choke performance
  - Max Impedance < 800 ohms
  - Mostly resistive

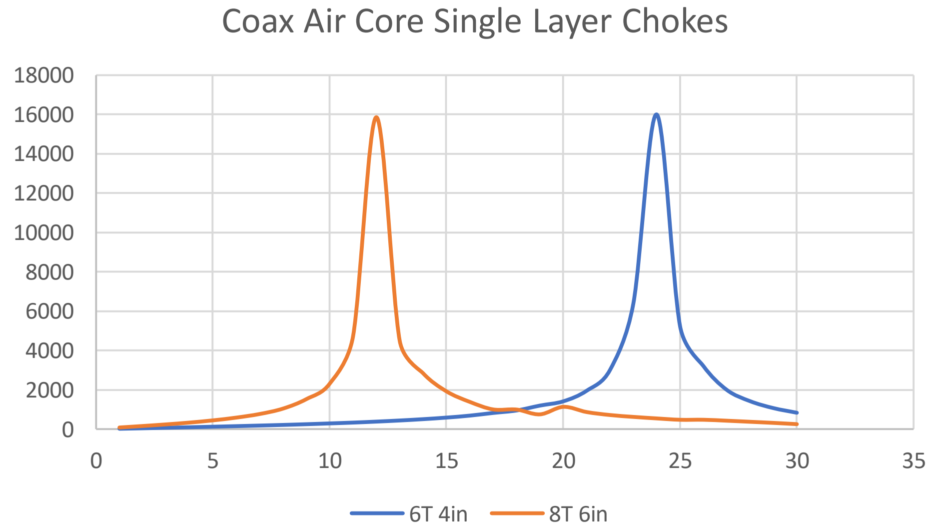
SWR < 1.08:1

Loss < 0.05 dB



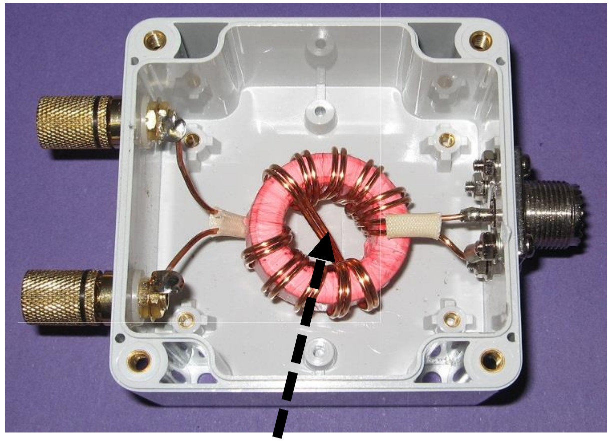
Coiled Coax "Ugly" Baluns

- Two basic types
  - Single layer
  - Bunched
    - Performance not as good as single layer
- Both types can achieve high impedance
  - Very high Q
    - Very small R and large X
    - Very narrow band
    - **SRF very sensitive to build parameters**
    - **System resonance can be a serious problem**
- Large and heavy
- Best "Bang for the Buck"



Transmission Line Transformer (TLT) Baluns

- Most common method of building Current Baluns & Chokes
- The transmission line can be coax or bifilar (parallel) wires
  - Line impedance is important for best performance
  - Line length << ¼ wavelength
  - Chose the line based upon impedance & power reqm'ts
- Use of coax yields very low SWR & insertion loss
- Only the Common Mode Current magnetizes the ferrite core
  - Minimizes Differential signa loss & core heating
- Choking Bandwidth:
  - Lowest useable freq: set by the inductance of the coil
    - More inductance lowers bottom cutoff frequency
    - More inductance requires more turns and/or higher permeability ferrite
  - Highest useable freq: set by **Self Resonant Frequency (SRF)** of the coil
    - More turns lowers upper frequency cutoff



Crossover done for layout, not performance reasons

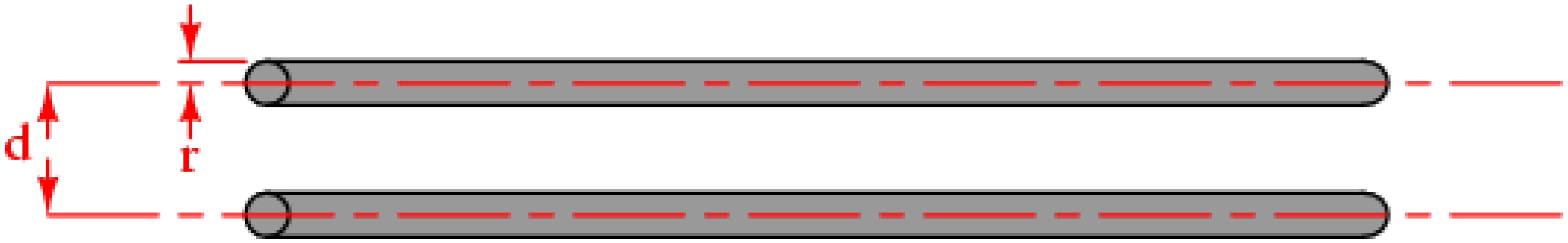
High Power Coax Chokes

- For high power applications

“MOAB”

Parallel Wire Transmission Line Impedance

- Optimal line impedance is determined by input & output impedances
  - Ex: a 50 to 200 ohm Balun requires a 100 ohm line



$$Z_0 = \frac{276}{\sqrt{k}} \log \frac{d}{r}$$

Where,

Z_0 = Characteristic impedance of line

d = Distance between conductor centers

r = Conductor radius

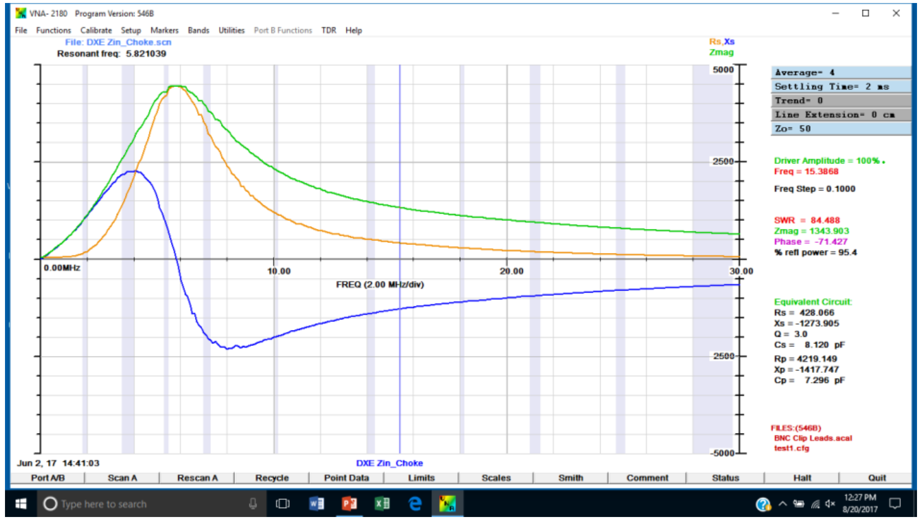
k = Relative permittivity of insulation between conductors

Design Tradeoffs

- Most Balun/Choke designs don’t provide both high Z *and* wide bandwidth
- Ferrite material
  - High Mu (61 & 77)
    - High loss
    - Narrow BW
    - High Z/turn
  - Low Mu (33 & 43)
    - Low loss
    - Wider BW
    - Low Z/turn
    - Frequent choice for HF Baluns/Chokes
- Power dissipation
  - For Current Baluns, Common Mode power is the critical spec
  - Single 2.4 in ferrite core may only be good for 5-10 watts of dissipation
  - Use stacked cores for more power dissipation

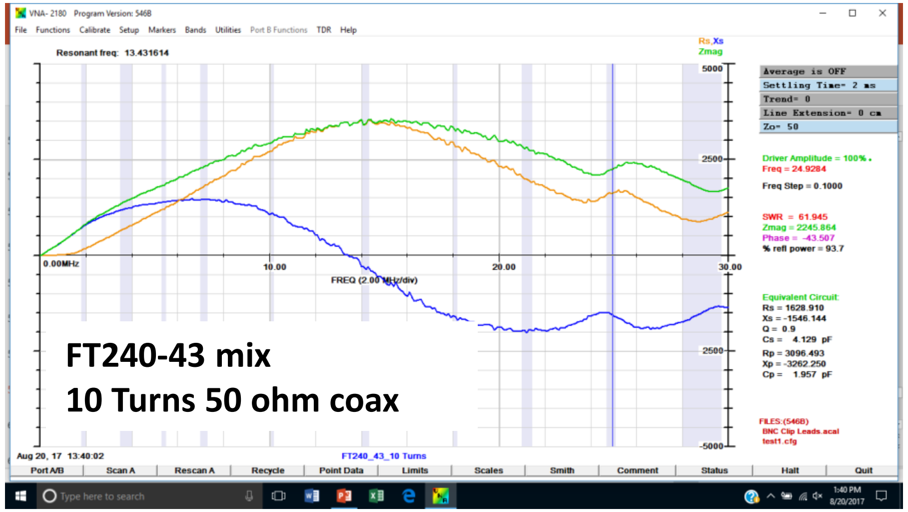
Examples: Common Mode Chokes

DX Engineering DXE-FCC050-H05-B

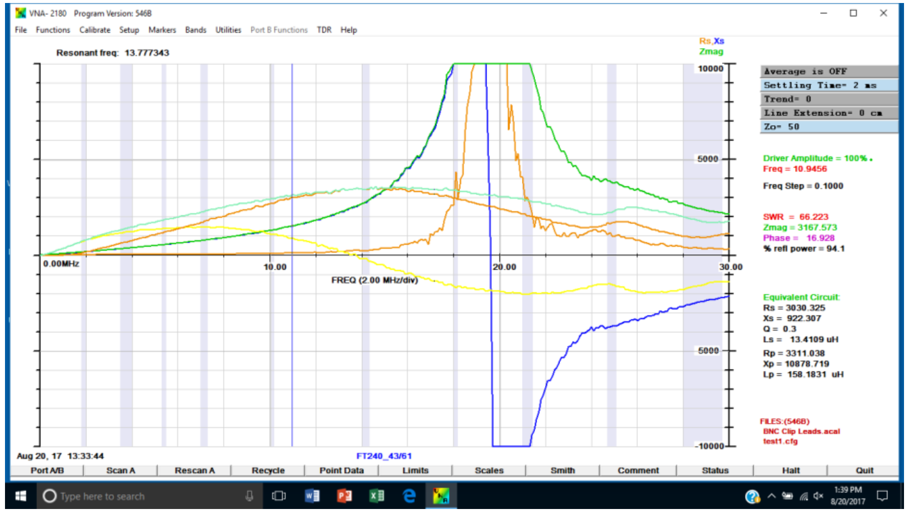


Homebrew Toroidal Choke

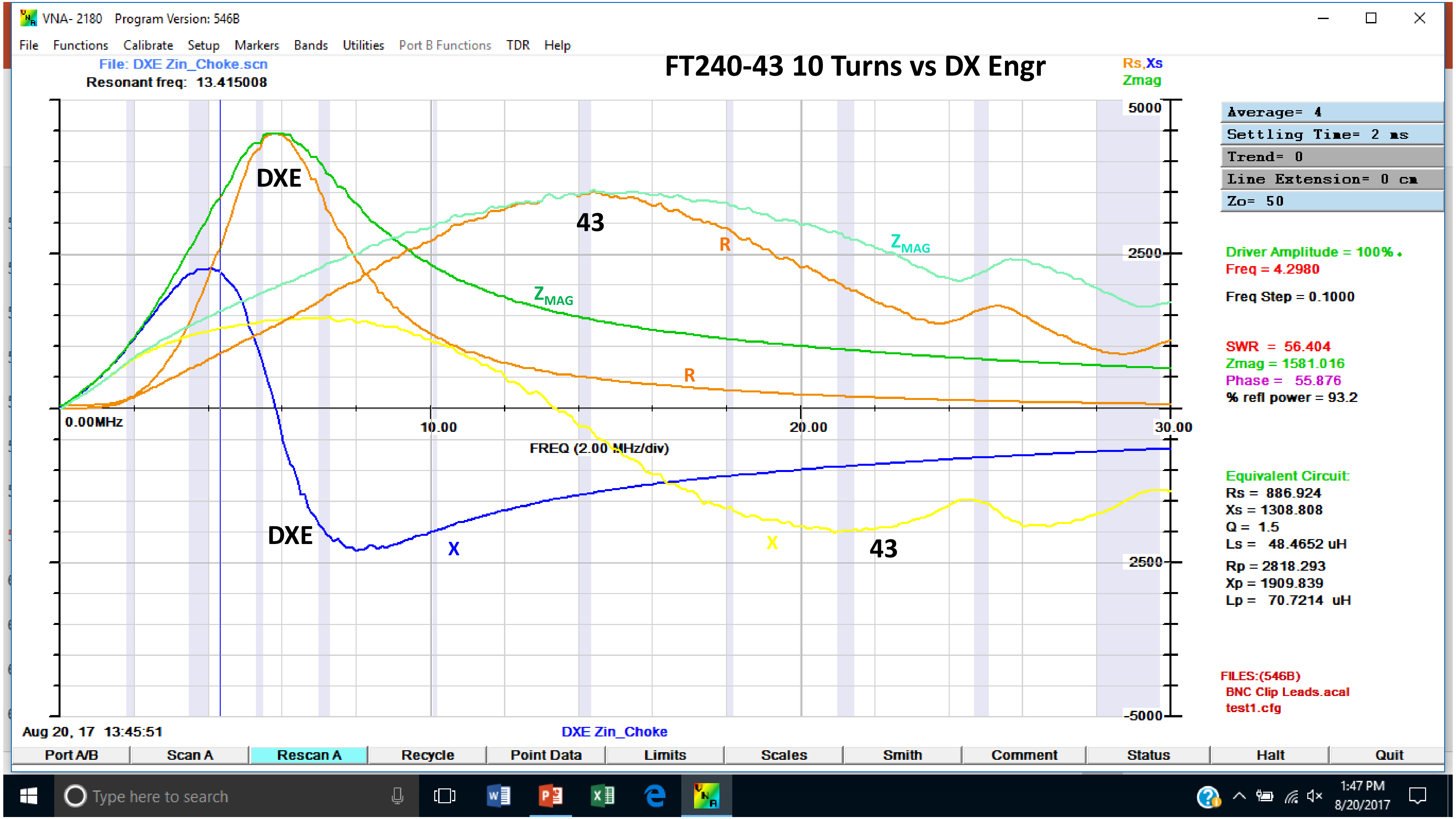
Homebrew Toroidal Choke



FT240-43 mix vs 61 mix



Examples: Common Mode Chokes



Ferrite & Powdered Iron (Iron Powder) Suppliers

- Amidon
  - Wide variety of products
  - Recently changed ownership
    - Used to have a good info sheet (=>?)
    - Used to have a minimum order requirement
  - Balun kits
    - Kit with handbook for extra $ => handbook is available free on the Internet
- Fair-Rite
  - <u>Producer</u> of ferrite & powdered iron products
    - Not a good source for "how to build ….." info (ie, don't call for help)
  - Evaluation (not balun or transformer) kits
  - Distributors (Mouser, …)
- Other Distributors: Palomar-Engineers, Radioworks, KF7P, …
  - May not be cost effective for some orders

Example: Using the Amidon Spec Sheet

What type core do I have?

1) Wrap 10 turns around core
2) Measure inductance at a frequency well below resonance (4.3 MHz):

$$L = 16.4\ \text{uH} = 0.0164\ \text{mH}$$

3) Calculate A_L = mH/1000 turns

$$= \text{mH}/10\ \text{turns} \times (n_{RATIO})^2$$

$$= \text{mH}/10\ \text{turns} \times 10{,}000$$

$$= 0.0164 \times 10{,}000$$

$$= 164\ \text{mH}/1000\ \text{turns}$$

Example: Using the Amidon Spec Sheet – cont'd

FERRITE TOROIDAL CORES

MATERIAL 43 — **Permeability 800**

Core number	O.D. (inches)	I.D. (inches)	Hgt. (inches)	ℓ_e (cm)	A_e (cm)^2	V_e (cm)^3	A_L Value mh/1000 turns
FT-23 -43	.230	.120	.060	1.30	.020	.027	158
FT-37 -43	.375	.187	.125	2.07	.072	.150	350
FT-50 -43	.500	.281	.188	2.95	.129	.380	440
FT-50A -43	.500	.312	.250	3.12	.150	.470	480
FT-50B -43	.500	.312	.500	3.12	.299	.930	965
FT-82 -43	.825	.520	.250	5.20	.243	1.260	470
FT-114 -43	1.142	.748	.295	7.30	.370	2.700	510
FT-140 -43	1.400	.900	.500	8.90	.790	7.000	885
FT-240 -43	2.400	1.400	.500	14.50	1.580	22.800	1075

MATERIAL 61 — **Permeability 125**

Core number	O.D. (inches)	I.D. (inches)	Hgt. (inches)	ℓ_e (cm)	A_e (cm)^2	V_e (cm)^3	A_L Value mh/1000 turns
FT-23 -61	.230	.120	.060	1.34	.020	.029	24.8
FT-37 -61	.375	.187	.125	2.15	.076	.163	55.3
FT-50 -61	.500	.281	.188	3.02	.133	.401	69.0
FT-50A -61	.500	.312	.250	3.68	.152	.559	75.0
FT-50B -61	.500	.312	.500	3.18	.303	.963	150.0
FT-82 -61	.825	.516	.250	5.26	.246	1.290	75.0
FT-114 -61	1.142	.750	.295	7.42	.375	2.790	80.0
FT-114A-61	1.142	.750	.545	7.42	.690	5.130	145.0
FT-140 -61	1.400	.900	.500	9.02	.806	7.280	140.0
FT-240 -61	2.400	1.400	.500	14.80	1.610	23.900	171.0

MATERIAL 67 — **Permeability 40**

Core number	O.D. (inches)	I.D. (inches)	Hgt. (inches)	ℓ_e (cm)	A_e (cm)^2	V_e (cm)^3	A_L Value mh/1000 turns
FT-23 -67	.230	.120	.060	1.34	.021	.029	6.0 Min
FT-37 -67	.375	.187	.125	2.15	.076	.163	18.0
FT-50 -67	.500	.281	.188	3.02	.133	.401	22.0
FT-50A -67	.500	.312	.250	3.68	.152	.559	24.0
FT-50B -67	.500	.312	.500	3.18	.303	.963	48.0
FT-82 -67	.825	.516	.250	5.26	.246	1.290	24.0
FT-114 -67	1.142	.750	.295	7.42	.375	2.790	25.4
FT-140 -67	1.400	.900	.500	9.02	.806	7.280	45.0
FT-240 -67	2.400	1.400	.500	14.80	1.610	23.900	55.0

MATERIAL 68 — **Permeability 20**

Core number	O.D. (inches)	I.D. (inches)	Hgt. (inches)	ℓ_e (cm)	A_e (cm)^2	V_e (cm)^3	A_L Value mh/1000 turns
FT-23 -68	.230	.120	.060	1.34	.021	.029	4.0
FT-37 -68	.375	.187	.125	2.15	.076	.163	8.8
FT-50 -68	.500	.281	.188	3.02	.133	.401	11.0
FT-50A -68	.500	.312	.250	3.68	.152	.559	12.0
FT-82 -68	.825	.520	.250	5.26	.246	1.290	11.7
FT-114 -68	1.142	.750	.295	7.42	.375	2.790	12.7

AMIDON Associates, INC. 240 Briggs Avenue, Costa Mesa, California 92626, U.S.A. • TEL. (714) 850-4660 • FAX (714) 850-1163

2-5

- On a mfg spec sheet, find the A_L that is closest to your measured value
- Core is 2.4 in diameter => Material = 61 (Actual A_L values can vary =/- 25%)

Conclusions

- When should a Balun/Choke be used
  - Answer1: When you suspect Common Mode Current is causing a problem
    - Not just because someone told you to use one
  - Answer2: With monoband antennas, try a different length of transmission line first
- What type of Balun/Choke should be used
  - Answers:
    - Usually a Current Balun/Choke
    - Voltage Baluns for high impedance antennas like end fed halfwaves
- Where should they be installed
  - Answer: Start with one at the antenna
- What should I observe after I install one
  - Answer: Problem gets better, gets worse, or doesn’t change at all
- It is best to know the impedance vs frequency of a Balun/Choke before you use it
  - Some antenna analyzers don’t have enough range (MFJ-259 limited to Z<600 ohms)