Pulsed Power Engineering
Materials & Passive Components and Devices

January 12-16, 2009

Craig Burkhart, PhD
Power Conversion Department
SLAC National Accelerator Laboratory

Materials & Passive Components and Devices Used in Pulsed Power Engineering

- Materials
  - Conductors
  - Insulators
  - Magnetic material
- Passive components and devices
  - Resistors
  - Capacitors
  - Inductors
  - Transformers
  - Transmission lines
  - Loads
    - Klystrons
    - Beam kickers

Materials

- Generally encounter three types of materials in pulsed power work
  - Conductors
    - Wires & cable
    - Buss bars
    - Shielding
    - Resistors
  - Insulators
    - Cables and bushing
    - Standoffs
    - Capacitors
  - Magnetic
    - Inductors, transformers, and magnetic switches
    - Ferrite and tape-wound

Calculating Resistance

- At low frequency, resistance (R) determined by:
  - $R = \rho\ell/A$ (ohm)
    - Material resistivity, ρ ($\Omega\cdot$cm)
    - Conductor length, ℓ (cm)
    - Conductor cross-sectional area, A (cm^2)
- At high frequency, effective conductor area decreased by "skin effect"
  - Conducted current produces magnetic field
  - Magnetic field induces eddy currents in conductor which oppose/cancel B
  - Eddy currents decay due to material resistance, allow conducted current/magnetic field to penetrate material
  - Skin depth, δ, is the effective conducted current penetration ($B = B_{applied}/e$)
  - $\delta = (2\rho/\mu\omega)^{1/2}$ (meters) for a current of a fixed frequency $\omega=2\pi f$,
    $= (6.6/f^{1/2})[(\mu_o/\mu)(\rho/\rho_c)]^{1/2}$ or
    $\approx (2t\rho/\mu)^{1/2}$ (meters) for a pulsed current of duration t (sec)
    - Material resistivity, ρ ($\Omega\cdot$m)
    - Copper resistivity, $\rho_c = 1.7 \times 10^{-8}$ ($\Omega\cdot$m)
    - Material permeability, μ (H/m)
    - Permeability of frees space, $\mu_o = 4\pi \times 10^{-7}$ (H/m)
  - Litz wire is woven to minimize skin effects

Resistivity of Common Materials

Material	Resistivity @ 20° C
Aluminum	2.62 μΩ•cm
Be-Cu	5.4 – 11.5 μΩ•cm
Brass (66% Cu, 34% Zn)	3.9 μΩ•cm
Copper (OFHC)	1.72 μΩ•cm
Copper (water pipe)	2.1 μΩ•cm
Graphite (typical)	1.4 mΩ•cm
Gold	2.44 μΩ•cm
Indium	9 μΩ•cm
Iron	9.71 μΩ•cm
Silver	1.62 μΩ•cm
Stainless Steel (typical)	90 μΩ•cm
Steel (0.5% C)	13 – 22 μΩ•cm
Water (purified)	2 X 10^7 Ω•cm (maximum)
Water (tap)	10^4 Ω•cm
Water/$CuSO_4$	25 Ω•cm (minimum)

Insulator Properties

- Insulators are used to isolate and support conductors of differing electric potential
- Typically characterized by two properties
  - Breakdown strength, E_{BD}, electric field which will arc through the material
  - Dielectric constant (relative), $\varepsilon_r = \varepsilon/\varepsilon_o$
- Regularly use solid, liquid and gaseous (and vacuum) insulators in pulsed power engineering

Solid Dielectrics

- Can be used as structural elements
- Breakdown through material is irreparable
- Can also arc along surface, flashover, typically at $E \approx 0.5\ E_{BD}$
- E_{BD} limited by material imperfections, voids, where corona can occur and gradually degrade material. Therefore E_{BD} decreases with increasing material thickness, as the probability of defects increases.
- 100 V/mil $< E_{BD} <$ 1 kV/mil (typical, >0.1") (kV/mil ~ 0.4 MV/cm)
- $2 < \varepsilon_r < 10$ (typical, excluding ceramic capacitor materials $\sim 10^3$)

Solid Dielectric Properties

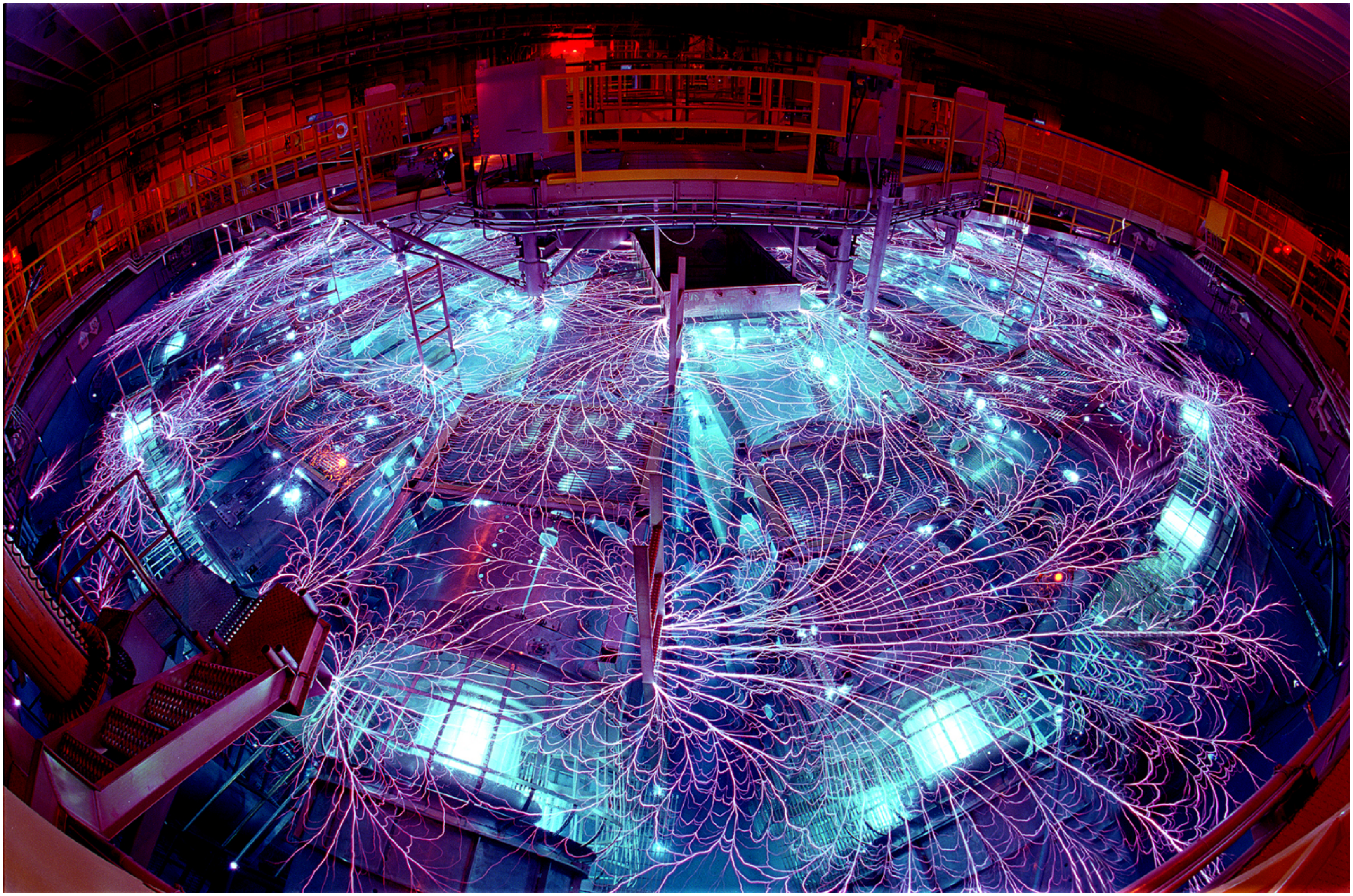
Material	Diel. Const. 60 Hz. ε	tan δ	Diel. Const. 1 MHz. ε	tan δ	Diel. Strength* V/mil
Aluminum Oxide	8.80	3.3(-4)	8.80	320	320
Barium Titanate	1250	0.056	1143	0.0105	75
Soda-Borosilicate Glass	4.97	-----	4.84	3.6(-3)	400
Epoxy (Epon RN-48)	4.50	0.05	3.52	0.0142	800
Polycarbonate	3.17	0.009	2.96	0.01	400
Acrylic	4.0	0.016	2.55	0.009	400
Polyimide	3.4	0.002	3.4	0.003	570
Polyvinyl Chloride	3.20	0.0115	2.88	0.016	400
PTFE (Teflon)	2.10	<5(-4)	2.10	<2(-4)	550
Polyethylene	2.26	<2(-4)	2.26	<2(-4)	450
Polypropylene	2.55	<5(-4)	2.55	<5(-4)	650
Paper	3.30	0.010	2.99	0.038	200

*Typical DC values for .10 inch thick samples

From NSRC Pulse Power Formulary

$Y(X) \equiv Y \bullet 10^X$

Dielectric "Pool": SNL Z-machine



Liquid Dielectrics

- Breakdown damage can be "healed"
  - Arcing may result in conductive (typically carbon) residue
  - Circulation will disburse residue, reduce concentration below threshold
  - Filtration/processing can remove contamination
- Oil is the most common liquid insulator used in pulsed power (you are not a pulsed power engineer until you have been up to your armpits in oil)
- Water and Ethylene Glycol are often used in PFLs and capacitors
  - High dielectric constants increase pulse length and energy storage
    - Water: $\varepsilon_r = 81$
    - Ethylene Glycol: $\varepsilon_r = 41$
  - Because of low resistivity, can only be used for pulse-charged applications
    - $RC = \rho\varepsilon \sim 2\ \mu s$ maximum for water at 20^o C (However, this can be increased to ~100 ms by mixing Ethylene Glycol, antifreeze, with the water and chilling the solution to near the freezing temperature.)
  - Breakdown strength
    - E_{BD} is weakly pulse length dependent (see Pulsed Power Formulary)
    - Typical pulsed operation: ~ 50 – 200 kV/cm (~half the strength of oil)

Dielectric Oils

- Mineral oils
  - Pulsed power work horse
  - Many trade names (e.g. Sontex, Diala AX), some with additives, electrical properties vary little
  - Polychlorinated Biphenyls (PCB) generally phased out in 60's, but may be present in older systems (new systems usually labeled as "PCB free")
  - Increasing concern about the toxicity/environmental impact of these oils
  - Some plastic and rubber compounds will swell if immersed in mineral oil
  - Hydroscopic (absorbs water), but takes a lot to significantly degrade properties and can be removed by heating
  - Properties also degraded by entrainment oil air (avoid centrifugal pumps)
  - For best performance, should be circulated, filtered, de-watered and de-aerated
  - Dielectric constant: $\varepsilon_r = 2.2$ (excellent match to many polymers)
  - Breakdown strength
    - E_{BD} is weakly pulse length dependent (see Pulsed Power Formulary)
    - Typical pulsed operation: ~ 100 – 400 kV/cm
    - Typical dc operation: ~40 kV/cm

Dielectric Oils (cont.)

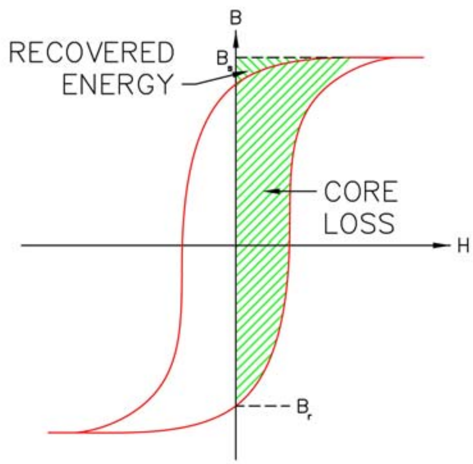
- Silicon oils
  - High quality
  - Expensive
- Vegetable oils: castor, rapeseed, canola, etc.
  - Increased usage
  - Low toxicity/environmental impact
  - Properties may vary significantly from mineral oils
    - High viscosity, may not be functional at ambient temperatures
    - May support bacterial growth
    - Different dielectric constants; castor ~ 4.5
- Other "oils" used in high value applications (e.g. capacitors)
    - Isopropyl biphenyl
    - benzyltoluene diphenylethane
    - phenyl xylyl ethane
    - tricresyl phosphate
    - ethyl hexyl phthalate

Gaseous Dielectrics

- Breakdowns cause no permanent damage
  - Used for high power switches; spark gaps, thyratrons
  - Produces gas ionization
  - Ion/electron recombination time ~ms (shorter at higher pressure)
- Dielectric constant: $\varepsilon_r = 1$ (low stored energy in stray capacitance)
- Corona (electrical discharge below the breakdown threshold) will ionize gas. This can produce chemical radicals (e.g. O_3) which can degrade system elements.
- Breakdown strength in air:
  - $E_{BD} \approx 25p + 6.7(p/d)^{1/2}$ (kV/cm)
    - Gas pressure, p (atm absolute)
    - Conductor spacing, d (cm)
  - Relative breakdown strength of gases:
    - Air 1.0
    - Nitrogen 1.0
    - SF_6 2.7
    - H_2 0.5
    - 30% SF_6, 70% Air 2.0

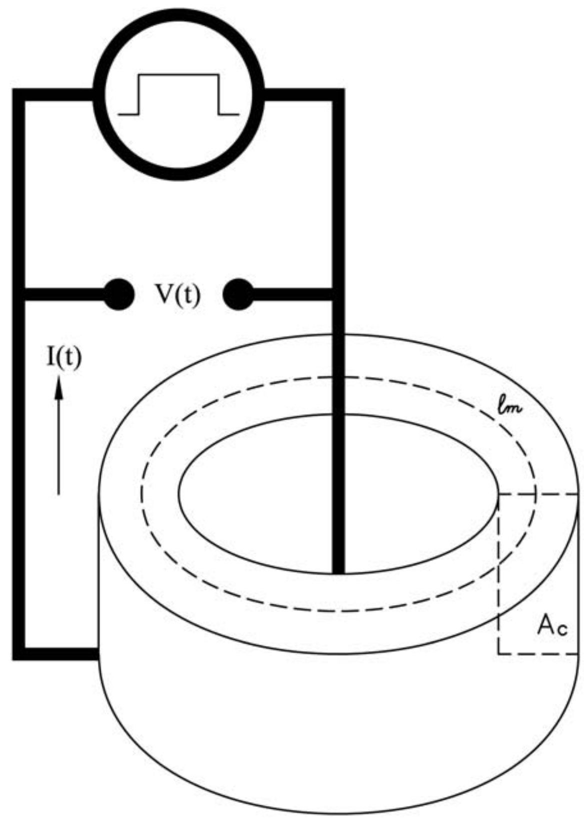
Magnetic Material Properties

- Permeability, μ
  - μ(H/m) = B(T)/H(A/m)
  - Often expressed as relative permeability, $\mu_r = \mu/\mu_o$ = B(G)/H(Oe)
    - $\mu_r \approx$ 25,000 for Fe, 400 for Carbon steel
  - Permeability of free space, $\mu_o = 4\pi \times 10^{-7}$ H/m
- Flux swing, ΔB
  - Change in flux density a material can support before it saturates ($\mu \rightarrow \mu_o$)
  - Typically from remnant flux (H=0), B_r, to saturation flux, B_s: $\Delta B = B_r + B_s$
- Hysteresis loop
  - Plot of B vs H
  - Slope is μ
  - Area is energy



Magnetic Material Properties (cont.)

- Faraday's law
  - $\int \mathbf{B} \bullet d\mathbf{A} = \int V\, dt$
  - $A_c\, \Delta B = V\tau$
    - Cross sectional area of core, A_c
    - Pulse voltage, V
    - Pulse duration, τ
- Ampere's law
  - $\int \mathbf{H} \bullet d\boldsymbol{\ell} = I$
  - $H = I/\ell_m$
    - Magnetizing current, I
    - Mean magnetic path length, $\ell_m = 2\pi\, (R_o - R_i) / \ln(R_o / R_i)$ (log mean circumference)

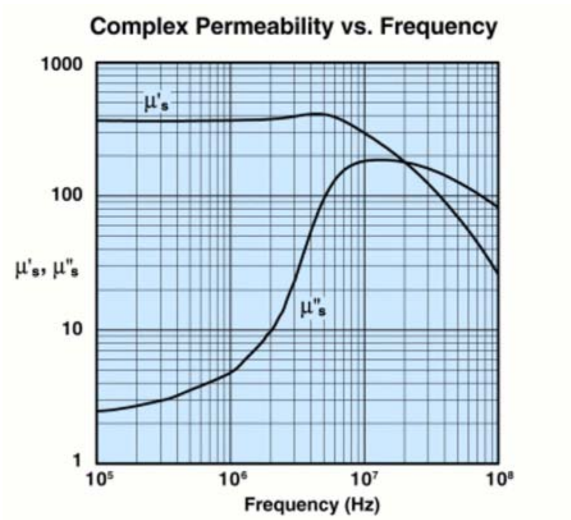


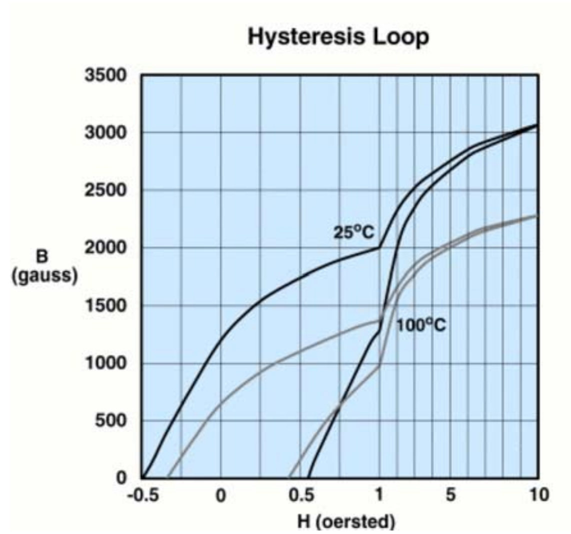
Magnetic Materials

- Two types of material are typically used
  - Ferrimagnetic materials: ferrite cores
    - μ_r: ~500 – 2000 (typical)
    - μ_r approximately constant to >MHz for some formulations
    - ρ: ~10^9 Ω•cm
    - ΔB: ~0.5 T
  - Ferromagnetic materials: tape-wound cores
    - ρ: ~10^{-5} Ω•cm
      - Eddy currents impede field penetration into material (skin effect)
      - Must be wound from thin (0.001") ribbon interleaved with insulator
      - Insulator does not have magnetic properties, effective area of magnetic material reduced by packing factor, η = insulator thickness/total tickness
    - μ_r: >10^4
    - μ_r strong function of frequency in MHz range for even best materials
    - ΔB: >3 T
- Hysteresis characteristics of any material can be linearized by adding a gap to the core

Ferrite

- Two dominant compositions
  - NiZn
    - Highest frequency response
    - High frequency transformers & chokes, magnetic switching, induction accelerator cores
    - CN20, CMD5005, PE-11B

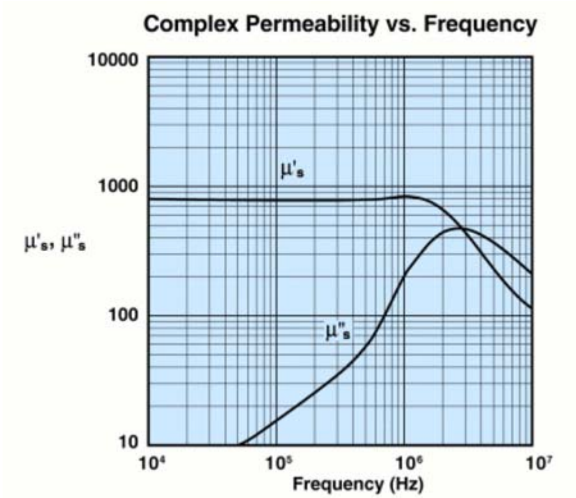


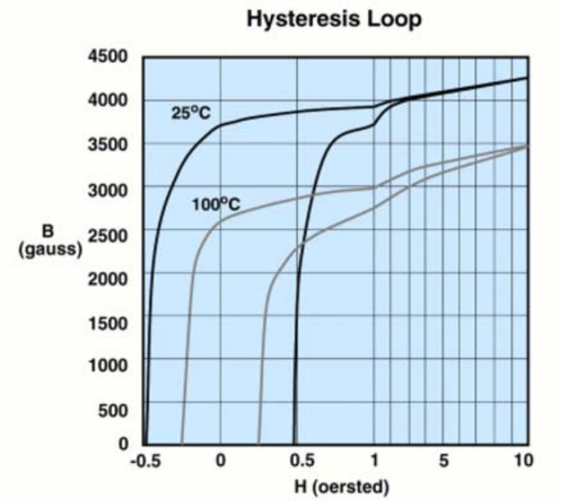


  - Fair-Rite 51
    - Low-loss
    - Modest frequency response (5 MHz)
    - Not square

Ferrite

- Two dominant compositions
  - MnZn
    - Larger ΔB
    - Switch-mode power supply transformers





  - Fair-Rite 85
    - Square loop

Tape Wound Core Materials

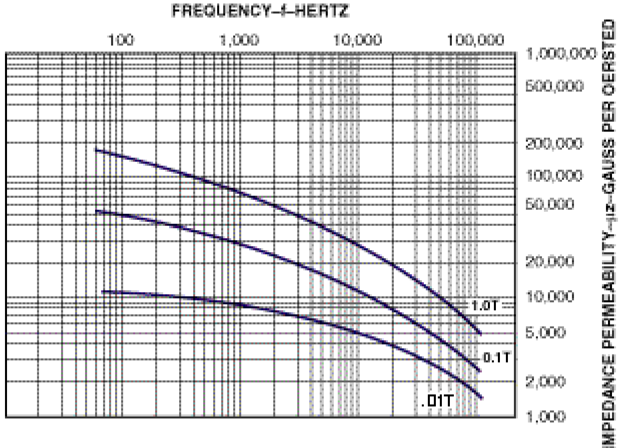
- Crystalline
  - Traditional core material
  - Common formulations: Si-Fe and Ni-Fe
  - Lowest cost
  - Poorest high frequency performance
- Amorphous (Metglas ©)
  - Developed in 70's/80's
  - Iron-based, Ni-Fe-based, and cobalt-based formulations
  - Low loss
  - Higher frequency response
  - Magnetic properties very dependent on annealing
  - Higher costs
- Nano-cyrstalline
  - Iron-based
  - Similar magnetic properties to Metglas
  - Zero magnetostriction

Crystalline Materials

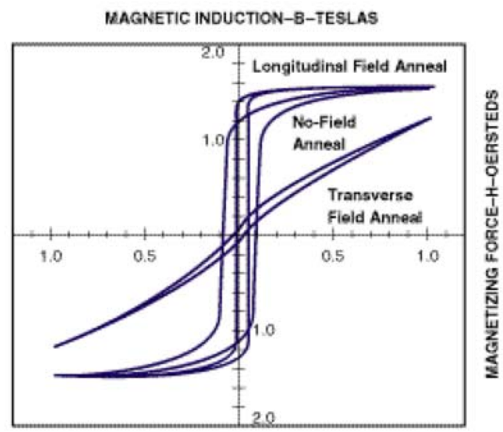
- Si-Fe
  - $\Delta B > 3$ T
  - $\mu_{max} > 25{,}000$
  - Low frequency applications, 1 – 16 mil thickness
- Ni-Fe
  - $\Delta B \sim 1.5$ T
  - $\mu_{max} > 25{,}000$ (>100,000 grain oriented material)
  - Thin material, <1 mil, good at higher frequencies, but expensive

Amorphous Materials

- 2605 SA1
  - Most common Fe-based material
  - Modest high frequency response
  - Lowest cost of the amorphous materials
  - $\Delta B \sim 3$ T
  - $\mu_{max} > 100{,}000$



Typical impedance permeability curves
Longitudinal field anneal



Typical dc hysteresis loops

Amorphous Materials

- 2605CO
  - Fe-based, with cobalt
  - Exceptionally square loop with longitudinal field annealing (lost tech ?)
  - Best material available for high frequency magnetic switching (0.7-mil)
    - $\Delta B = 3.3$ T
    - $\mu_{max} \sim 100{,}000$ (dc)
    - $\mu_{max} \sim 6{,}000$ (1 μs saturation)
    - $\mu_{max} \sim 1{,}000$ (0.1 μs saturation)
- 2714A
  - Co-based
  - Very square, very low loss
  - Best high frequency characteristics
  - $\Delta B = 1$ T
  - $\mu_{max} \sim 500{,}000$ (dc)

Nano-crystaline Materials

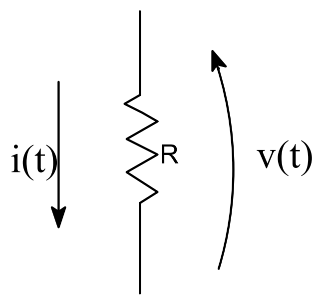
- Similar high frequency permeability and squareness as 2605CO
- $\Delta B \sim 2$ T
- $\mu_{max} \sim 60{,}000$ (dc)
- Major suppliers
  - Hitachi “Finemet”
  - Vacuumschmelze
  - “Russian”
- Hitachi makes excellent cores (including toroids)
  - Well annealed
  - Well constructed (ceramic insulation)

Passive Components and Devices

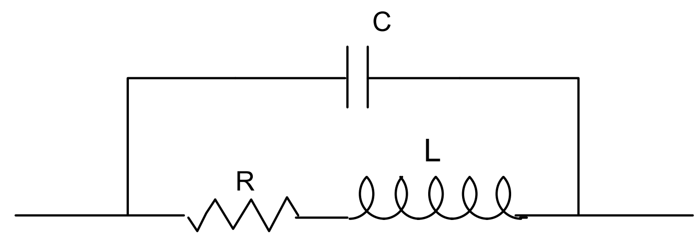
- Resistors
- Capacitors
- Inductors
- Transformers
- Transmission lines
- Loads
  - Klystrons
  - Beam kickers

Resistors

- Resistor behavior



$$v(t) = Ri(t)$$



High-Frequency Equivalent Circuit

Resistor Types

- Film
  - Commonly available
  - Inexpensive
  - Low active material mass → low energy capacity
    - 1W carbon film: ~3 J
    - 1W metal film: ~1 J
  - High voltage film resistors often have a helical pattern → high inductance
    - Alternative, non-inductive serpentine pattern (Caddock)
  - SMD
    - Usually trimmed with an "L-cut", introduces inductance
    - Tend to arc (and fail) at trim, due to $V = L\, dI/dt$
- Wire wound
  - Very inductive
  - Large power types (e.g. 225 W) can support large pulsed voltages, but if maintained at high voltage dc, will corona and eventually fail

Resistor Types (cont.)

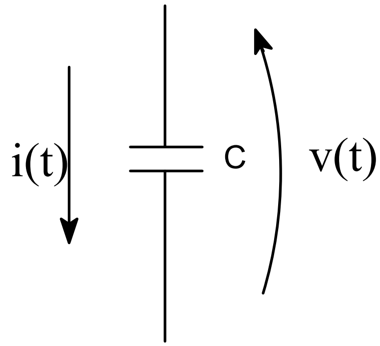
- Composition
  - Large active material mass → large energy handling capacity
  - Carbon Composition
    - 2W "standard" no longer manufactured
    - Voltage and power capacity varies by value
      - 2W: ~80 J, >2 kV repetitive, ~10 kV non-repetitive
  - Ceramic Composition
    - Ohmite OX/OY
    - Even better than carbon comps
    - 2W: ~20 kV non-repetitive
  - Bulk ceramic
    - Stackpole → US Resistor → Kanthal Globar / Carborundum → Cesewid → Kanthal Globar, but also Asian and European manufacturers
    - Vary composition for high voltage, high average power, and high peak power
    - Special coatings for immersion in oil (prevents resistance change)
    - Terminal shape and application critical for long life (corona prevention)
    - Increase average power capacity, ~7X, by flowing water through bore

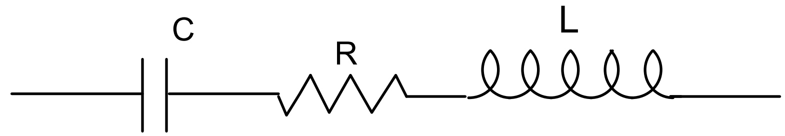
Resistor Types (cont.)

- Water resistors
  - Typically constructed with insulating tubing (plastic, flexible or rigid, or glass) envelope which contains water with electrodes at each end
  - May be sealed, resistance usually not very stable, or recirculating which can be accurately adjusted
  - Resistivity strongly dependent on water temperature
  - “Salt” is added to provide carriers
    - $CuSO_4$
    - Borax, environmentally benign
    - NaCl
    - KCl
  - Current density on electrodes limited by carrier density (solubility limits)
  - Exceeding $j_{critical}$ (740 mA/cm^2 for $CuSO_4$) → electrode erosion and/or electrolysis
  - Large specific energy deposition → heating → shock wave
- Beam sticks
  - High power but high cost

Capacitors

- Capacitor behavior





High-Frequency Equivalent Circuit
ESR ≡ parasitic resistance
ESL ≡ parasitic inductance
DF ≡ dissipation factor = RωC

$$q = CV$$

$$i(t) = C\frac{dV(t)}{dt} \quad : \quad \langle i \rangle = C\frac{\Delta V}{\Delta t}$$

$$V = \frac{1}{C}\int i(t)dt$$

Capacitor Types

- Coaxial cable
  - Often acts as capacitor unintentionally
  - $C = \tau/Z$ (transit time/impedance)
- Electrolytics
  - Lossy above ~kHz
  - Limited use in pulsed power, except slow circuits
- Mica
  - High quality
    - Stable
    - Low loss
  - Energy density: ~0.01 J/cm^3
  - Limited distribution, usually made to order
- Water
  - High energy density
  - Due to limited resistivity, only useful in short pulse applications
  - Not commercially available

Capacitor Types (cont.)

- Ceramic
  - Available to 50 kV
  - High average current types are available
  - Energy density ~0.025 J/cm^3
  - Lifetime: ?
  - Capacitance varies with voltage and temperature
  - Stability characterized by "class"
    - I, NPO, COG: most stable
    - II, X7R, Y5P: more variation
    - III: capacitance may decrease 50% at rated voltage

Film Capacitors

- Most commonly used capacitor type for pulsed power applications
- Parameters
  - Voltage: to 100 kV (typically)
  - Current: to 0.25 MA
  - Lifetime: function of
    - Dielectric voltage stress: life α E^x, typically $5 < x < 9$
    - Temperature: life is halved for every 10^o C increase (polypropylene)
    - Voltage reversal (pulse discharge): dV/dt relative to dielectric relaxation time
- Construction
  - Dielectric materials
    - Paper (wicks “oil”)
    - Polymers
      - Polyester (Mylar®)
      - Polypropylene, High Crystalline Polypropylene (HCPP) best
      - Hazy films wick “oil”
    - Oil/fluid (see page 9&10)
    - Combinations of the above

Film Capacitors (cont.)

- Construction (cont.)
  - Conductors
    - Foil
      - Aluminum typical
      - High currents
      - Extended foil (instead of tabs) designs for very high current
    - Metalization of dielectric films
      - Lower cost
      - Decrease volume
      - Can be made "self-healing", defects in <2% of film
        - » Internal breakdown in film ablates metalization: isolates defect
        - » Breakdown energy controlled by controlling metalization
          - Pattern
          - High resistivity metalization, to 0.2 $k\Omega/\square$
  - Fabrication
    - Wind (precision winding machines) on mandrel, annular
    - Flatten
    - Interconnect: series/parallel sections, usually <10 kV/section
    - Package
    - Impregnate

Film Capacitors (cont.)

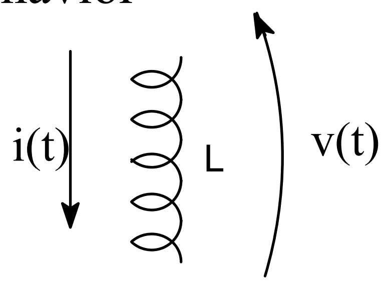
- Film/Foil construction
  - Standard for HV pulse discharge caps
  - Energy density:
    - ~0.02 J/cm^3, typical
    - To ~1 J/cm^3, for high energy density applications (short life)
  - Life
    - Scales as V^7 for a given design
    - >20 year or 10^{10} pulses possible, 10^4 to 10^5 more typical for high power caps
- Metalized film construction
  - Higher ESR
    - Lower current capacity
    - Metalization pattern can be tailored to increase current capacity
    - Can be combined with foil to increase current capacity
  - Energy density:
    - 0.1 to 0.3 J/cm^3, typical
  - Life
    - Scales as V^9 for a given design
    - >20 year or 10^{10} pulses possible

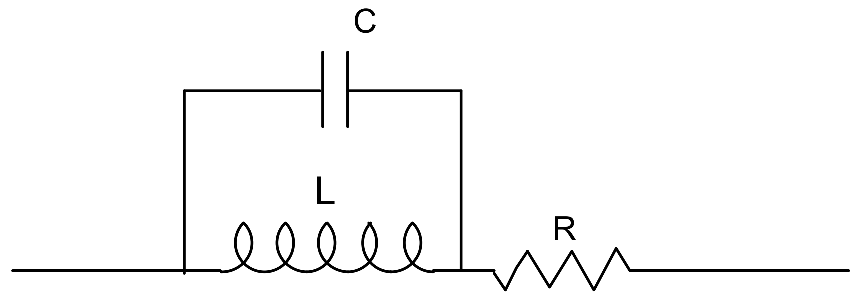
Component Websites

- Capacitors
  - NWL: http://www.nwl.com
  - Illinois Capacitor: http://www.illcap.com/
  - Cornell-Dubilier: http://www.cornell-dubilier.com/film.htm
  - Dearborn: http://www.dei2000.com/
  - Seacor: http://www.seacorinc.com/
  - Electronic Concepts: http://www.ecicaps.com/
  - Novacap: http://www.novacap.com/index.html
  - CSI: http://www.csicapacitors.com/index.asp
  - GA/Maxwell: http://www.maxwellcapacitors.com/
  - WIMA: http://www.wima.com/en_index.php
- Resistors
  - EBG Resistors: http://www.ebgusa.com/
  - RCD Components: http://www.rcdcomp.com
  - HVR Advanced Power Components: http://www.hvrapc.com
  - International Resistive Co.http://www.irctt.com
  - Kanthal Globar: http://www.globar.com
  - Caddock Resistors: http://www.caddock.com

Inductors

- Inductor behavior



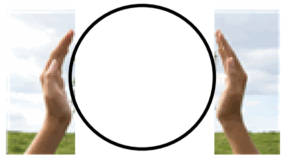


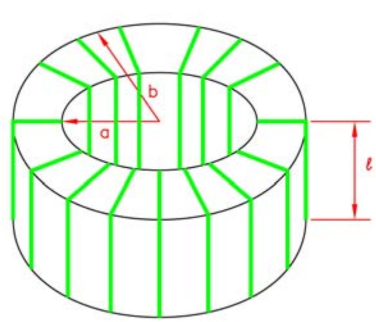
High-Frequency Equivalent Circuit

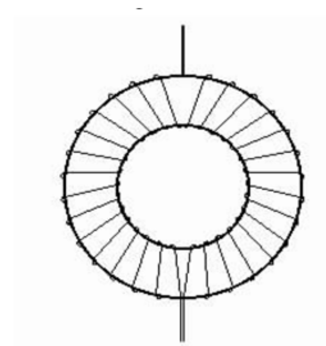
$$V(t) = L\frac{di(t)}{dt} \quad : \quad \langle V \rangle = L\frac{\Delta i}{\Delta t}$$

$$i(t) = \frac{1}{L}\int V(t)dt$$

Inductor Types

- Coaxial cable
  - Often acts as inductor unintentionally
  - $L = \tau Z$ (transit time•impedance)
- Current loop
  - 10 μH = 
  - $L = N^2 (a/100)\,[7.353 \log(16a/d) - 6.386]$ (μH)
    - N turns
    - On radius of a (inch)
    - Of d (inch) diameter conductor, ($a/d > 2.5$)
- Toroid
  - Closed field lines, minimize interaction with adjoining components
  - $L = (N^2 \mu \ell / 2\pi) \ln(b/a)$ (H)
    - N turns
    - Toroid outer radius, b (m)
    - Toroid inner radius, a (m)
    - Toroid length/thickness, ℓ (m)
  - Double ended for HV

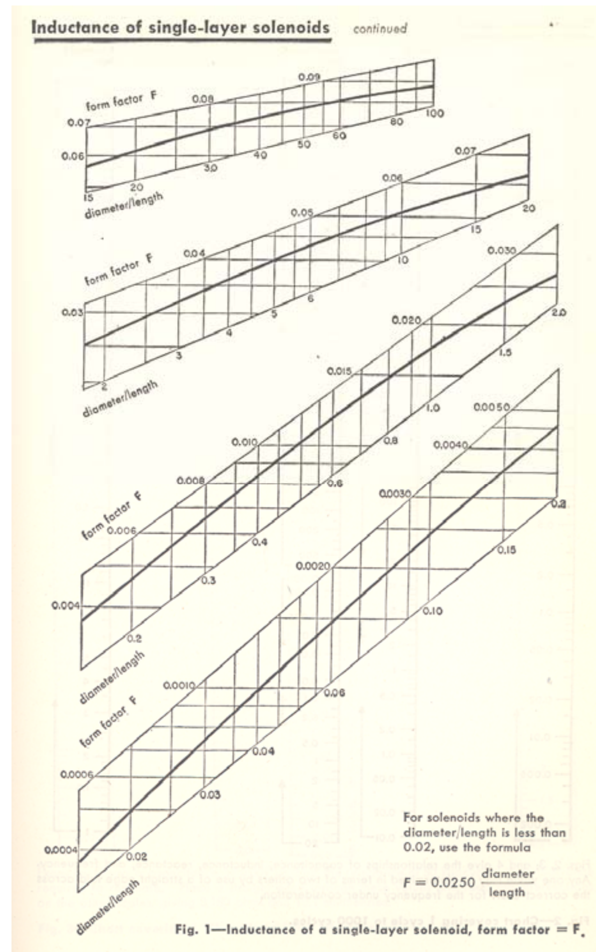




DOUBLE ENDED TORUS

Inductor Types

- Solenoid
  - Ideal: $L = N^2 \mu \pi r^2 / \ell$ (SI)
  - Typical: $L = N^2 [r^2/(9r + 10\ell)]$ (μH)
  - Generally: $L = F N^2 d$ (μH)
    - Single-layer solenoid
    - N turns
    - Radius: r
    - Diameter: d
    - Length: ℓ

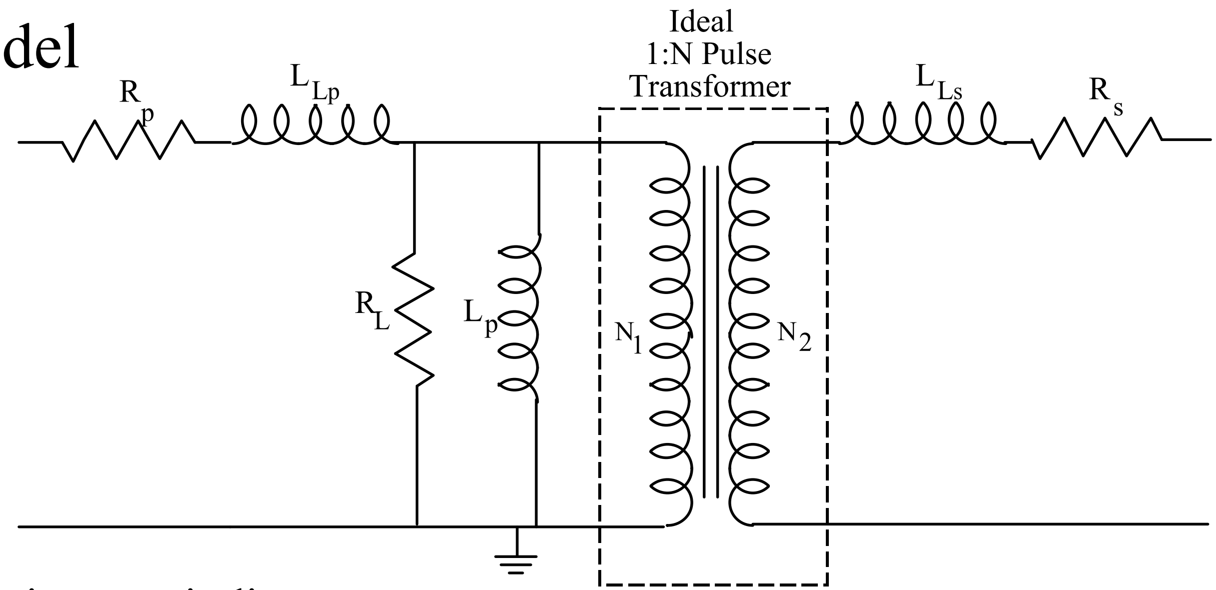


Inductors

- Permeability
  - Air core: μ_o
    - Constant, independent of frequency and current (subject to parasitic effects)
    - Low permeability
  - "Cored" (i.e. filled with magnetic material)
    - $V\tau$ constraint
    - $\mu = f(\omega, I)$
    - μ_r as high as $>10^5$
  - Compromise: gapped core
- Quality factor
  - $Q = \omega L / ESR$
  - Energy loss per cycle / total stored energy
- Commercial inductors are generally made "to order"
  - Magna Stangenes (Stangenes Industries)

Transformers

Transformer model



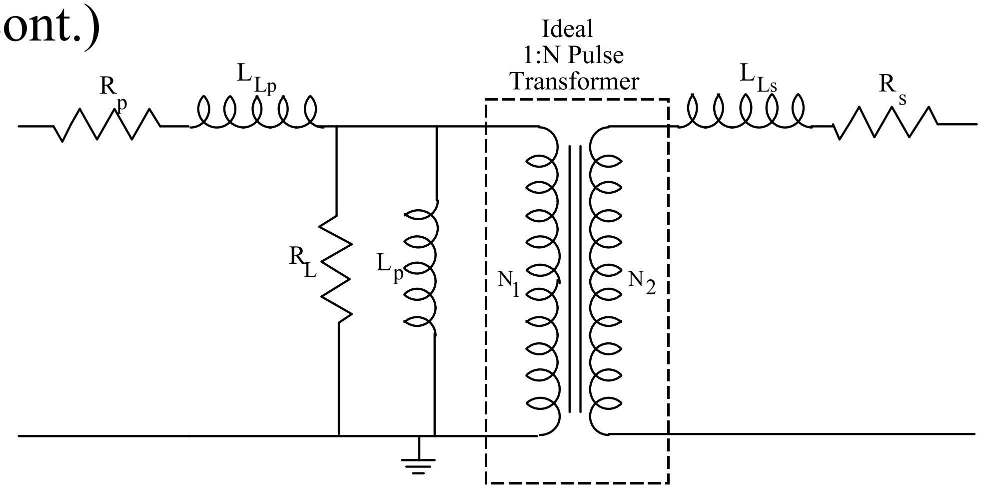
Equivalent Circuit

Where:

- R_p = resistance of primary winding
- R_s = resistance of secondary winding
- R_L = magnetic core loss
- L_p = inductance of primary winding (measured with secondary winding open)
- L_s = inductance of secondary winding (measured with primary winding open)
- L_{Lp} = leakage inductance of primary winding (measured with secondary shorted)
- L_{Ls} = leakage inductance of secondary winding (measured with primary shorted)
- leakage inductance is due to flux not linked by both primary and secondary windings
- $N_1:N_2$ = 1:N = turns ratio of ideal transformer

Transformers

- Transformer model (cont.)



$$\text{Primary Circuit Load} = \frac{Z_{secondary}}{N^2}$$

$$V_{secondary} = NV_{primary}$$

Other parameters:

k= coefficient of coupling between primary and secondary inductors
M = mutual inductance between two inductors

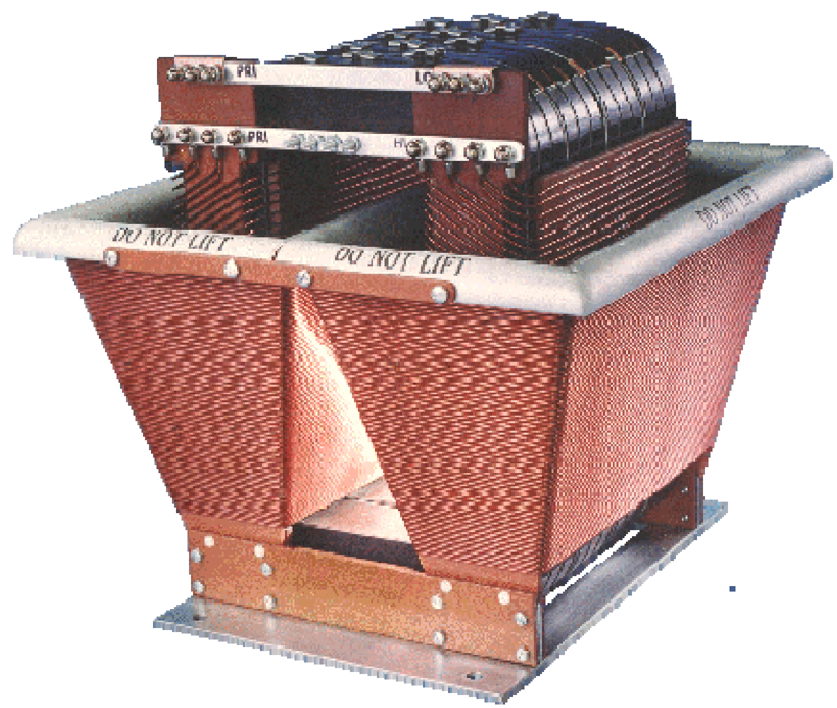
$$M = k\sqrt{(L_p L_s)}$$

$$L_{Lp} = (1-k)L_p$$

$$L_{Ls} = (1-k)L_s$$

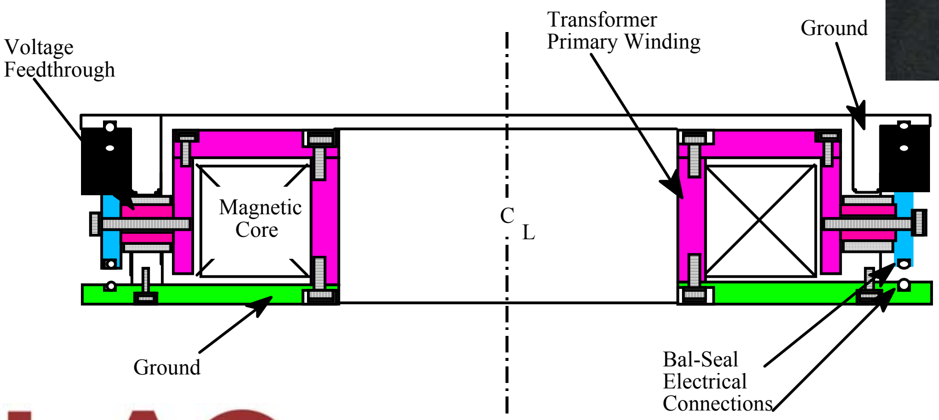
Pulse Transformers

- Functions
  - Voltage gain
  - Impedance matching
  - Teach humility
- Core
  - Material limitations
    - $V\tau$ constraint
    - $\mu = f(\omega, I)$
  - Typically gapped
- Stray capacitance
  - Primary to secondary
    - In series with leakage inductance
    - Operate below self-resonance
  - Secondary inter-winding
    - Load secondary
- Commercial pulse transformers are generally made to order

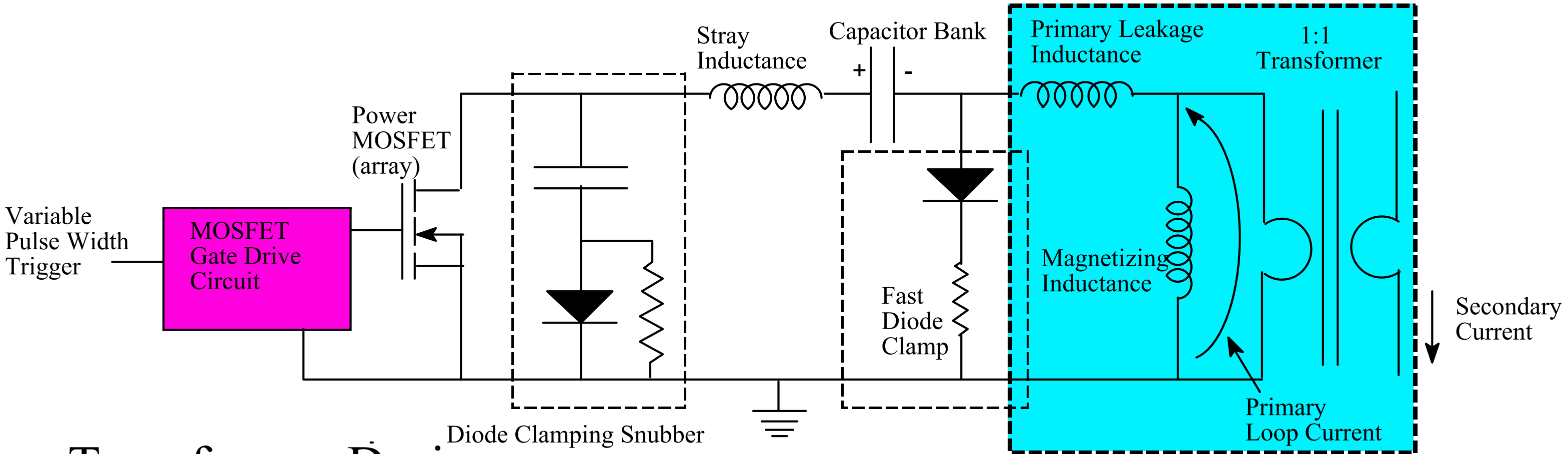


Stangenes Industries klystron transformer

Inductive Adder Transformer Design Example



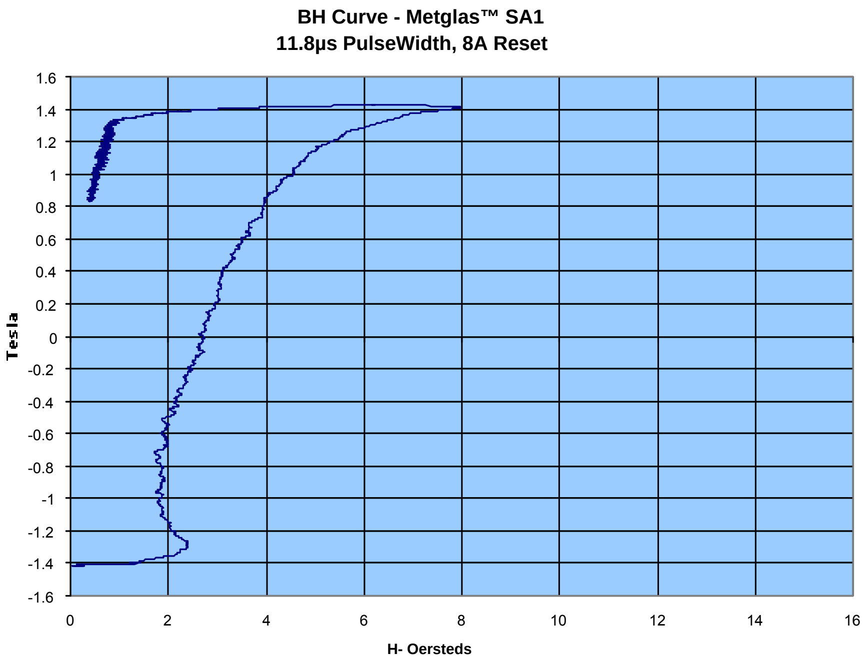
Inductive Adder Transformer Design Example

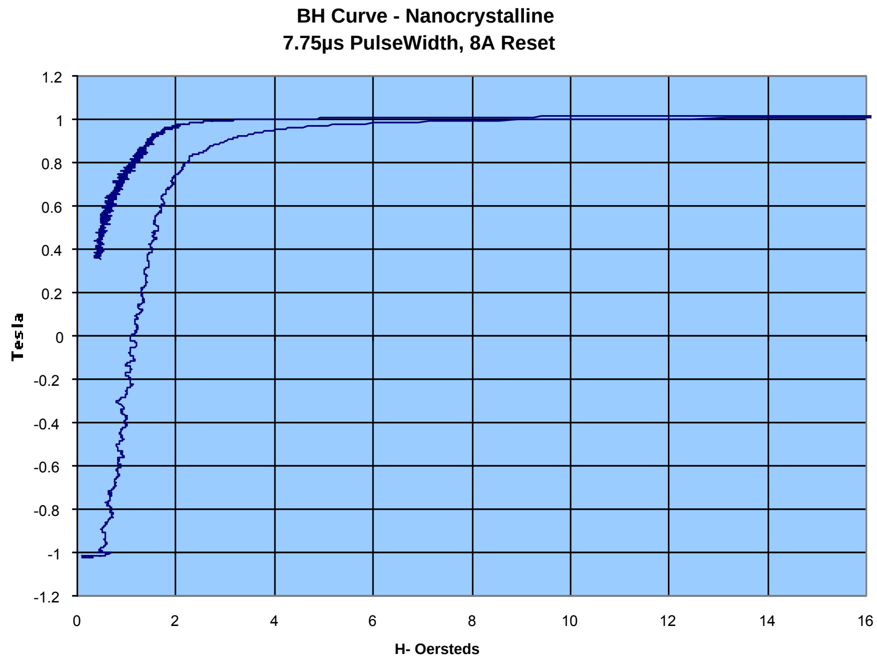


- Transformer Design
  - Select transformer geometry
    - Want a very high coefficient of coupling between primary and secondary
      - Single turn primary that totally encloses magnetic core
  - Select magnetic core material
    - Want low magnetizing current and leakage inductance so μ_r must be large
    - Magnetic core should never saturate during burst (use large safety factor)
    - Selected annealed MetGlass™ 2605-S3A
      - pulsed $\mu_r \sim 8000$
      - $\Delta B > B_{SAT}$ to - $B_r \sim 2.8$ T; use 0.5 T w/o interpulse reset
      - $\Delta\tau = 30\text{ ns} + 30\text{ ns} + 110\text{ ns} + 130\text{ ns} = 300\text{ ns}$

Inductive Adder Transformer Design Example

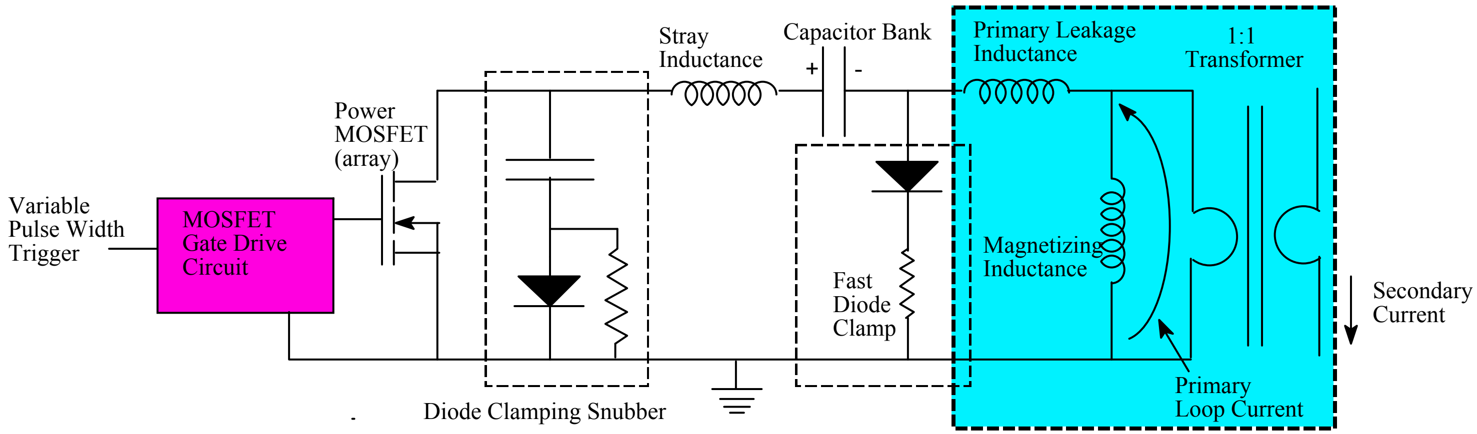
Pulsed BH Curve Data for Metglas™ SA1 and Nanocrystalline Magnetic Cores





Material	V-s with reset	V-s with reset disconnected
Metglas™ SA1	6.84 x 10-3	6.05 x 10^{-3}
Nanocrystalline (longitudinal anneal)	4.89 x 10^{-3}	3.70 x 10^{-3}

Inductive Adder Transformer Design Example



$$\Delta\tau = \frac{NA_m \Delta B}{V_{avg}} = \frac{NA_m \Delta B}{<V>}$$

$$A_m = \frac{300ns}{0.5T} 720V = 4.3 \times 10^{-4} m^2$$

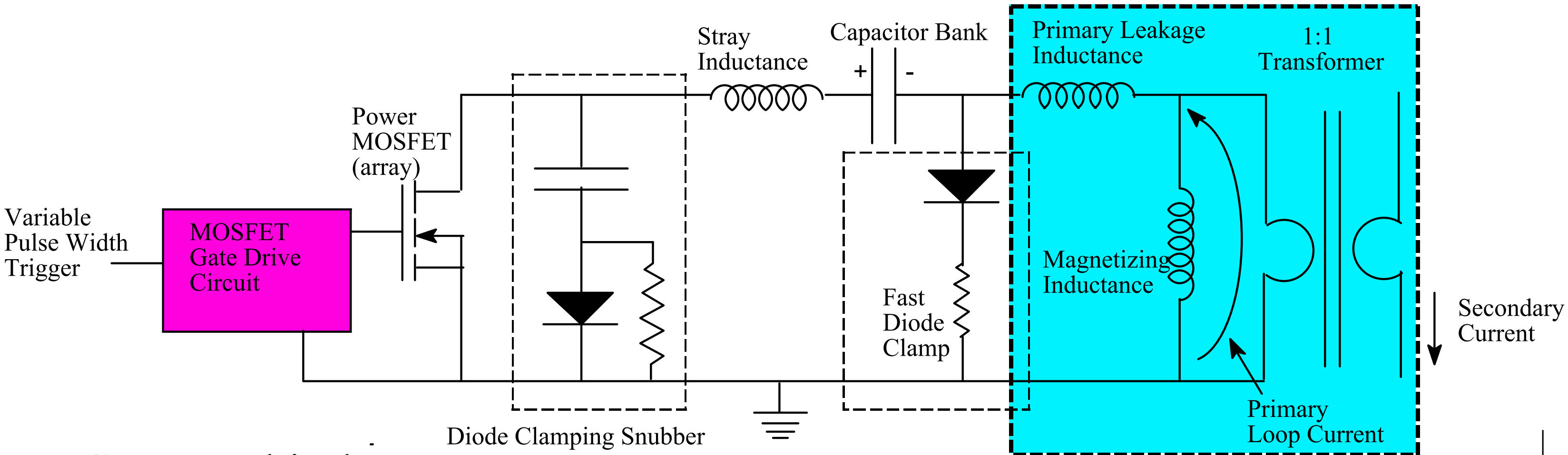
$$A_m = A_c(PF)$$

$$A_c \approx 6.2\text{x}10^{-4} m^2 \quad \text{for PF} \sim .7$$

Where:

- A_m is cross-section area of the magnetic core
- Ac is cross-section area of total core
- PF is core packing factor
- V_{avg} is the average voltage across the transformer primary winding
- ΔB is the total available flux swing in the magnetic core
- Δτ is the required hold-off time for the magnetic core
- N is the number of turns on the primary

Inductive Adder Transformer Design Example



- Saturated inductance

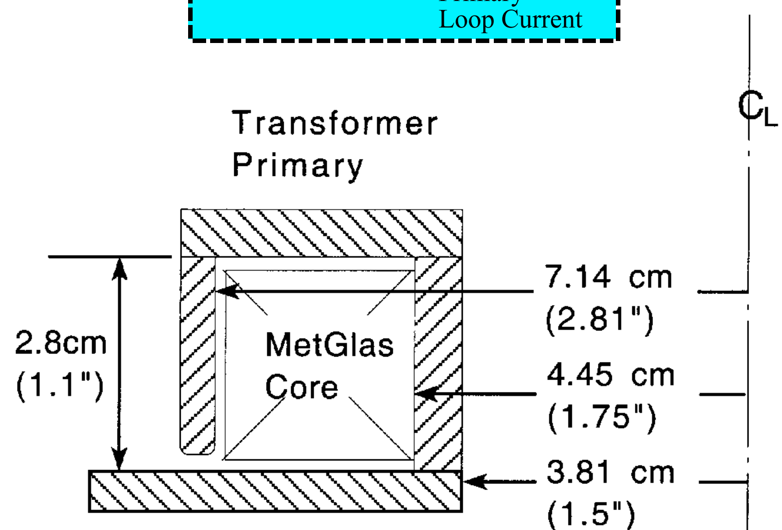
$$L_{SAT} \sim 200nH/_{m}\left(\frac{1.1m}{39.4}\right)\ell n\frac{7.14}{4.45}$$

$$L_{SAT} = 2.65nH$$

- Magnetization Current

$$H_c \sim \frac{100A}{m} = \frac{I_m}{l_m} \quad @\frac{\Delta B}{\Delta\tau} \sim 2T/\mu s$$

$$I_m \sim \frac{100A}{m}(.36m) \sim 36A$$



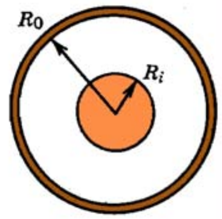
l_m = Mean Magnetic Length ~ 0.36 meters

Common Transmission Line Geometries

TABLE 9.3 Properties of Common Transmission Lines, TEM Modes[a]

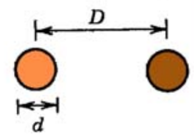
1 Coaxial transmission line:

$$\mathscr{C} = 2\pi\varepsilon/\ln(R_0/R_i)$$
$$\mathscr{L} = (\mu/2\pi)\ln(R_0/R_i)$$
$$Z_0 = (\sqrt{\mu/\varepsilon}/2\pi)\ln(R_0/R_i)$$



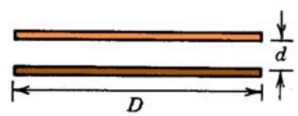
2 Two-wire transmission line

$$\mathscr{C} = \pi\varepsilon/\cosh^{-1}(D/d)$$
$$\mathscr{L} = \mu/\pi \cosh^{-1}(D/d)$$
$$Z_0 = (\sqrt{\mu/\varepsilon}/\pi)\cosh^{-1}(D/d)$$



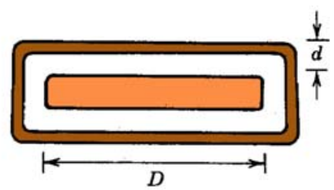
3 Isolated parallel plates ($d \ll D$)

$$\mathscr{C} = \varepsilon D/d$$
$$\mathscr{L} = \mu d/D$$
$$Z_0 = \sqrt{\mu/\varepsilon}(d/D)$$



4 Stripline ($d \ll D$)

$$\mathscr{C} = 2\varepsilon D/d$$
$$\mathscr{L} = \mu d/2D$$
$$Z_0 = \sqrt{\mu/\varepsilon}(d/2D)$$



[a] $\mathscr{C}$ = capacitance per unit length (farads/meter); $\mathscr{L}$ = inductance per unit length (henries/meter); Z_0 = characteristic impedance (ohms).

Discrete Element Transmission Line Approximation

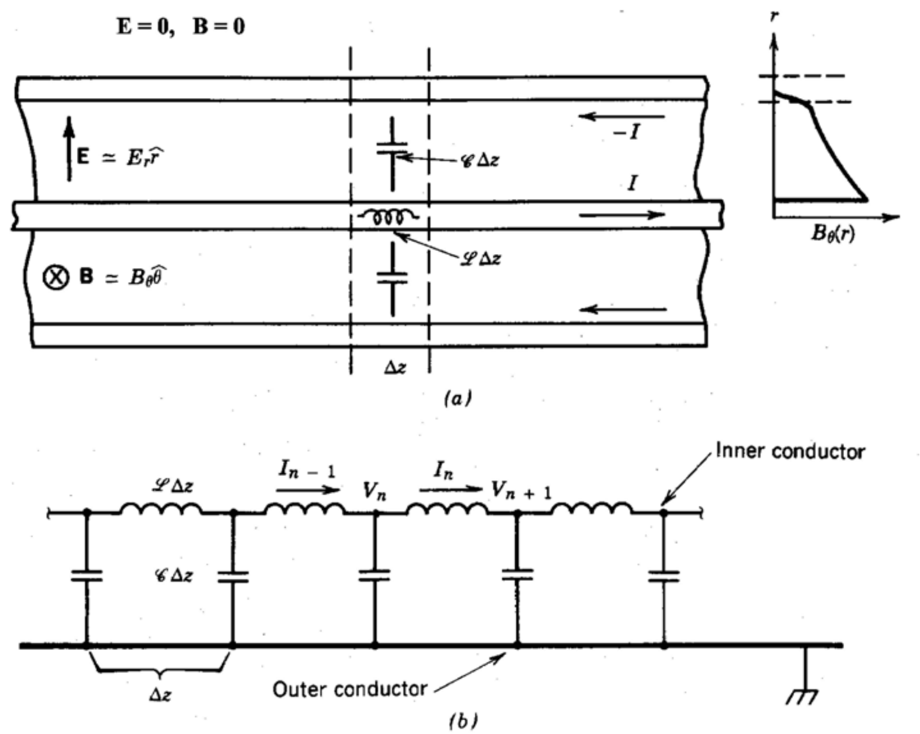


Figure 9.29 Coaxial transmission line. (*a*) Physical basis for lumped circuit element model of TEM wave propagation. (*b*) Lumped circuit element analog of a coaxial transmission line.

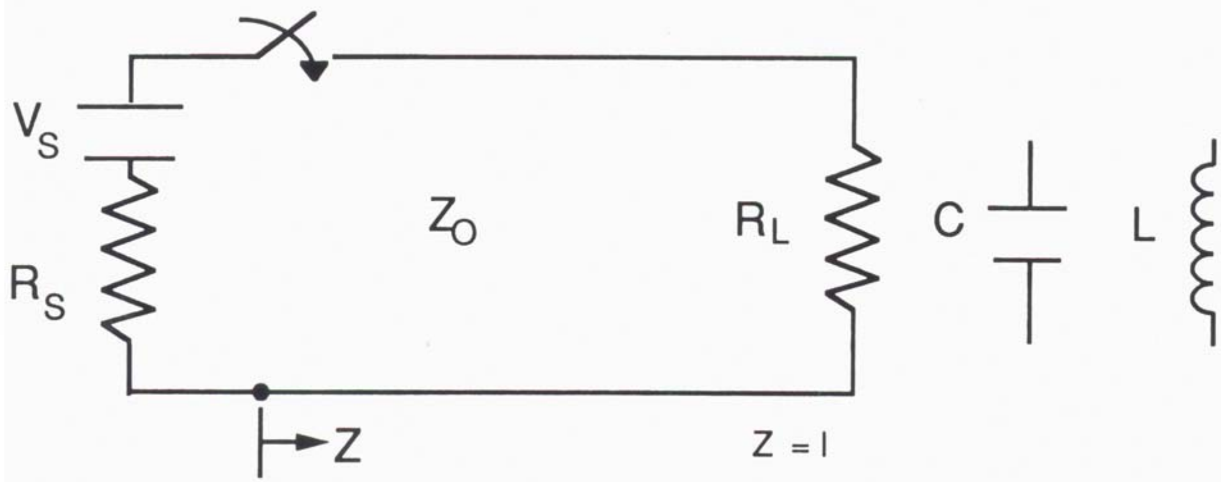
Transmission Line Terminations

- Matched: $R = Z_O$, $V_T = V_I$, $V_R = 0$
- Open: $R = \infty$, $V_R = V_I$, $V_T = 0$
- Short: $R = 0$, $V_R = -V_I$, $V_T = 0$
- General
  - $V_T = (2 R V_I) / (R + Z_O)$
  - $V_R = V_I [(R - Z_O) / (R + Z_O)]$
  - $I_T = (2 V_I) / (R + Z_O)$
  - $I_R = V_R / Z_O = (V_I / Z_O)[(R - Z_O) / (R + Z_O)]$

- V_I : Incident voltage
- V_R : Reflected voltage
- V_T : Transmitted voltage
- $V_I = V_T - V_R$
- I_I : Incident current = V_I /Z_O
- I_R : Reflected current
- I_T : Transmitted current
- $I_I = I_T + I_R$

Transmission Line Termination (cont.)

$$V_+ = \frac{V_S Z_O}{Z_O + R_S} \qquad \underset{t\to\infty}{V_L} = \frac{V_S R_L}{R_S + R_L}$$



Reflection Coefficient $\rho = \dfrac{Z_L - Z_O}{Z_L + Z_O}$

Transmission Coefficient $T = \dfrac{2Z_L}{Z_L + Z_O}$

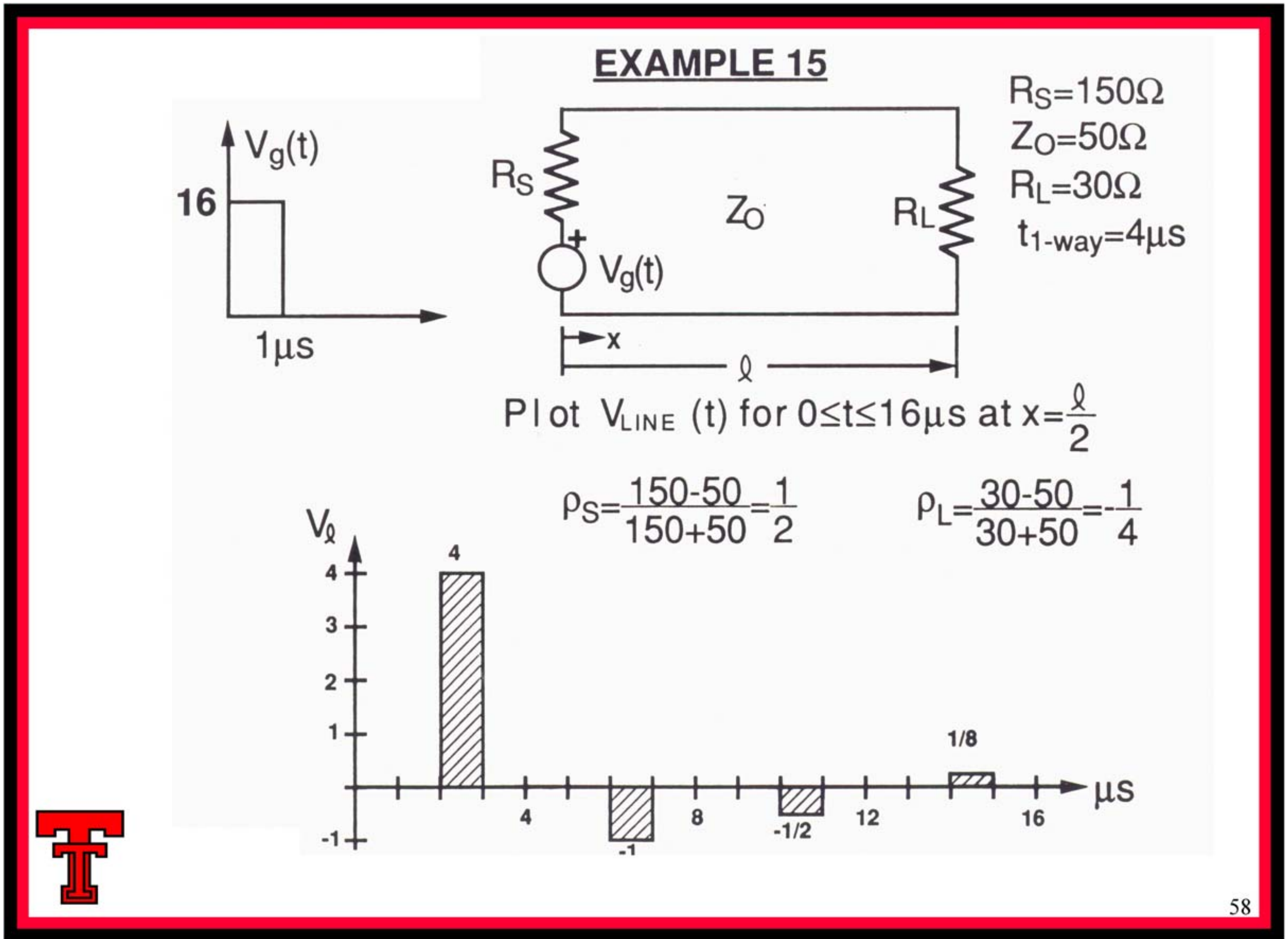
$T - \rho = 1$

Note: Reflection coefficient for current $\rho_I = -\rho$

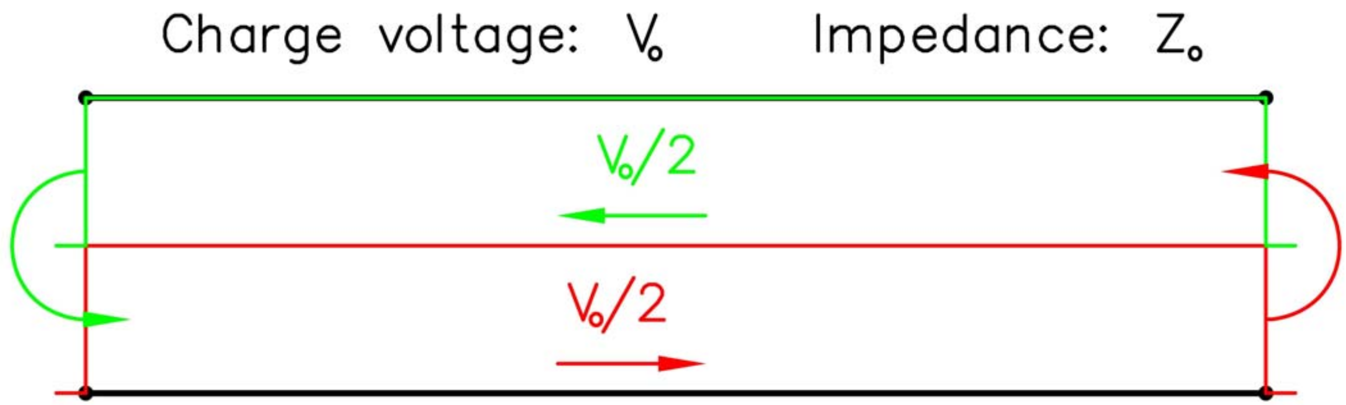
K-EMF-39 **REFLECTION AND TRANSMISSION COEFFICIENTS**

57

Transmission Line Termination (cont.)

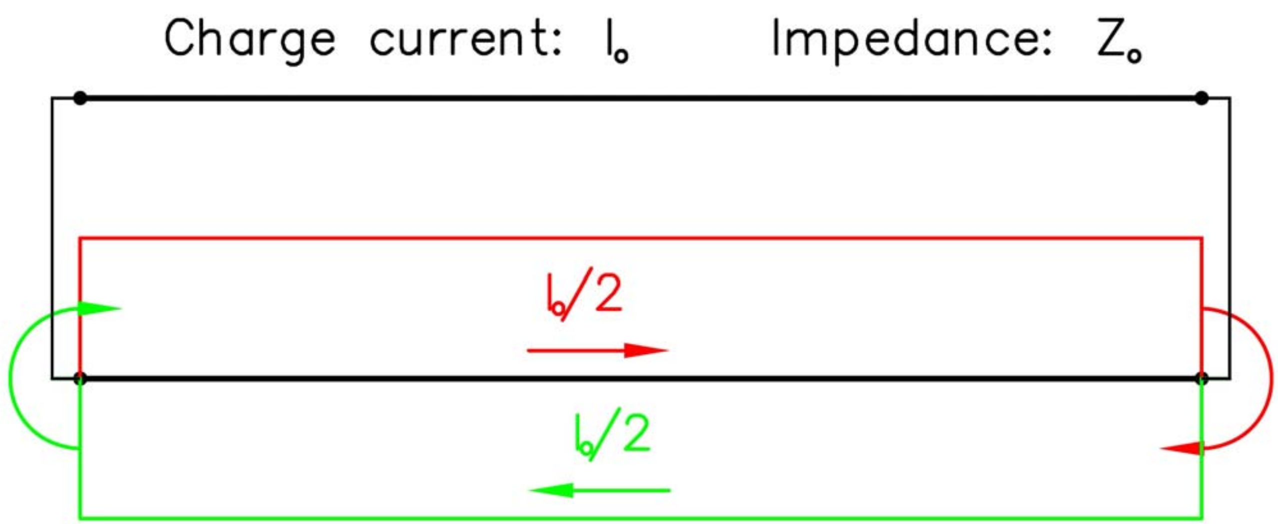


Voltage Charged Transmission Line



- Section of transmission charged to voltage, V_o, “open” at both ends
- Equivalent model
  - Propagating wave of voltage $V_o/2$ traveling left to right
  - Encounters open at end of line and reflects, same polarity and equal magnitude
  - Sum of left and right going waves is V_o
  - When left to right going wave reaches open at end it reflects and replenishes right to left going wave
- Implication: if line is connect to matched load, $V_T = V_I = V_o/2$

Current Charged Transmission Line



- Section of transmission charged to current, I_o, “shorted” at both ends
- Equivalent model
  - Propagating wave of current $I_o/2$ (and voltage $I_o Z_o/2$) traveling left to right
  - Encounters open at end of line and reflects, opposite polarity and equal magnitude
  - Sum of left and right going waves is $I = I_o$ and $V = 0$
  - When left to right going wave reaches short at end it reflects and replenishes right to left going wave
- Implication: if line is connect to matched load, $I_T = I_I = I_o/2$ and $V_T = I_o Z_o/2$

Klystrons

- Purpose: convert low frequency electrical power to radio frequency EM power
- Capable of producing very high peak Rf power, up to ~100 MW, with a nearly constant phase and amplitude for the bulk of the output pulse
- Amplifiers: output regulation limited by input regulation
  - Low level Rf (LLRF)
  - Beam acceleration voltage
    - Rf phase α beam voltage
    - 0.1^{o} phase stability typically required
    - Necessitates beam voltage stability to <50 V on >100 kV, 0.05% (LCLS 10 ppm)
  - Beam focusing fields (typically solenoid current)
- Electron beam devices operating with space-charge limited emission
  - $I_{beam} = \mu V^{1.5}$
  - Perveance, μ, typically ~10^{-6}
  - $Z = V/I = 1/\mu V^{0.5}$
  - $P_{beam} = VI = \mu V^{2.5} = P_{Rf}/0.6$ (typical)

Beam Kickers

- Purpose: selectively deflect a portion of a charged particle beam into an alternative transport channel
- Two general types
  - Lumped inductance
    - Kicker is an electromagnet
    - Beam deflected by magnetic field
    - High current modulator
  - Transmission line
    - Kicker presents a fixed impedance to the modulator
    - Terminated into a matched impedance to avoid reflections
    - Typically uses both E and B to deflect beam
    - No intrinsic rise/fall time, can be used in systems with small inter-bunch spacing