Pulsed Power Engineering: Materials & Passive Components, and Devices

Pulsed Power Engineering
Michigan State University
February 3 – 7, 2025

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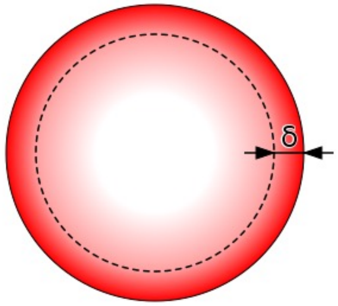
Materials & Passive Components and Devices Used in Pulsed Power Engineering

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

Materials

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

Calculating Resistance



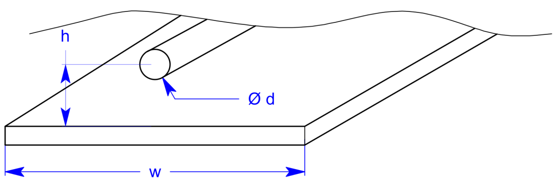
- At low frequency, resistance (R) determined by:
  - $R = \rho\ell/A$ (ohm)
    - Material resistivity
    - ρ (Ω•cm), Conductor length, ℓ (cm)
    - Conductor cross-sectional area, A (cm^2)
- At high frequency, effective conductor area decreased by "skin effect"
  - Conducted current produces magnetic field
  - Magnetic field induces eddy currents in the conductor whose fields oppose the original field, but also push the original current to the outside of the conductor.
  - Eddy currents decay due to material resistance, allow conducted current/magnetic field to penetrate material
  - Skin depth, δ, is the effective conducted current penetration depth within which 67% (1-1/e) of the current flows.
  - $\delta = (2\rho/\mu\omega)^{1/2}$ (meters) for a current of a fixed frequency $\omega=2\pi f$, or $\delta \approx (2t\rho/\mu)^{1/2}$ (meters) for a pulsed current of duration t (sec)
    - Material resistivity, ρ (Ω•m)
    - Material permeability, μ (H/m)
  - $\delta = (6.6/f^{1/2})[(\rho/\rho_c)/(\mu/\mu_o)]^{1/2}$ (cm)
    - Normalized resistivity, (ρ/ρ_c) , copper resistivity, $\rho_c = 1.7 \times 10^{-8}$ (Ω•m)
    - Relative permeability, $\mu_r = (\mu/\mu_o)$, permeability of free space, $\mu_o = 4\pi \times 10^{-7}$ (H/m)
  - Litz wire is woven insulated strands to minimize skin effects
  - Proximity effect is similar cause but few simple formulae
  - You need a complete circuit to transmit power, a supply and return
    - Wires that have an electrical length > rise time are transmission lines

Resistivity of Common Materials

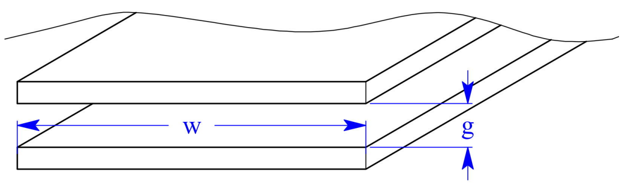
Material	Resistivity @ 20^o C
Aluminum	2.62 μΩ•cm
Be-Cu	5.4 – 11.5 μΩ•cm
Brass (66% Cu, 34% Zn)	3.9 μΩ•cm
Copper (OFHC)	1.72 μΩ•cm
Copper (water pipe)	2.1 μΩ•cm
Graphite (typical)	1.4 mΩ•cm
Gold	2.44 μΩ•cm
Indium	9 μΩ•cm
Iron	9.71 μΩ•cm
Silver	1.62 μΩ•cm
Stainless Steel (typical)	90 μΩ•cm
Steel (0.5% 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)

Completing Circuits

- Connections using pairs of conductors
  - Consider repetitive normal force, peak fault current and rms current
- Wire above a return plane, plane much wider that separation, no magnetic materials, skin depth small compared to wire diameter or plane thickness
  - $L \sim (\mu_0\, l/2\pi) \cosh^{-1} (2\, h/d)$ [H]
  - Length l [m], Height above plane h [m], diameter of wire d [m]
  - For low frequency, modify h by h + skin depth
  - Two wires same diameter, by symmetry distance between wires is now 2h



- Two planes with separation much less that width of plane, no magnetic materials, skin depth small compared to plate thickness
  - $L \sim (\mu_0\, l\, g/w)$ [H]
  - Length l [m], spacing between planes h [m], width of planes w [m]
  - For low frequency, modify g by g + 2 x skin depth



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, gaseous, and vacuum insulators in pulsed power engineering

Solid Dielectrics

- Can be used as structural elements
- Breakdown through material is irreparable
- Can arc along surface, flashover, typically at $E \approx 0.5\ E_{BD}$ (surface finish and geometry dependant)
- E_{BD} limited by material imperfections, voids, where corona can occur and gradually degrade material. Therefore $E_{BD(ave)}$ decreases with increasing material thickness, as the probability of defects increases.
- 100 V/mil < E_{BD} < 1 kV/mil (typical, >0.1")

  40 kV/cm < E_{BD} < 0.4 MV/cm
- $2 < \varepsilon_r < 10$ (excluding ceramic capacitor materials ~10^3)
  - Barium titanate capacitors do not work well in pulse applications due to ferroelectric coefficient (applied electric field makes a dimensional change) because they shake apart, strontium titanate has a much smaller ferroelectric effect

Solid Dielectric Properties [1]

Material	Diel. Const. 60 Hz. ε	$\tan\delta$	Diel. Const. 1 MHz. ε	$\tan\delta$	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

$$\tan\delta = \frac{\sigma}{\omega\varepsilon} = \frac{1}{R_P * \omega C_p}$$

[1] From Pulse Power Formulary

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

Liquid Dielectrics

- Breakdown strength can be comparable to solids
  - Greatly reduced by introduction of contaminants
  - Contaminants in applications with DC fields can cause issues when they collect to form a chain bridging high field regions
- 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)

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)
    - However, it takes a lot of absorbed water to significantly degrade properties
    - Absorbed water can be removed by heating
  - Properties also degraded by air entrainment (avoid centrifugal pumps)
  - For best performance, should be circulated, filtered, de-watered and de-aerated
  - Dielectric constant: ε_r = 2.2 (excellent match to many polymers)
  - Breakdown strength
    - E_{BD} is weakly pulse length dependent, $\alpha\ t^{0.33}$ (see Pulsed Power Formulary)
    - Typical pulsed operation: ~ 100 – 400 kV/cm
    - Typical dc operation: ~40 kV/cm

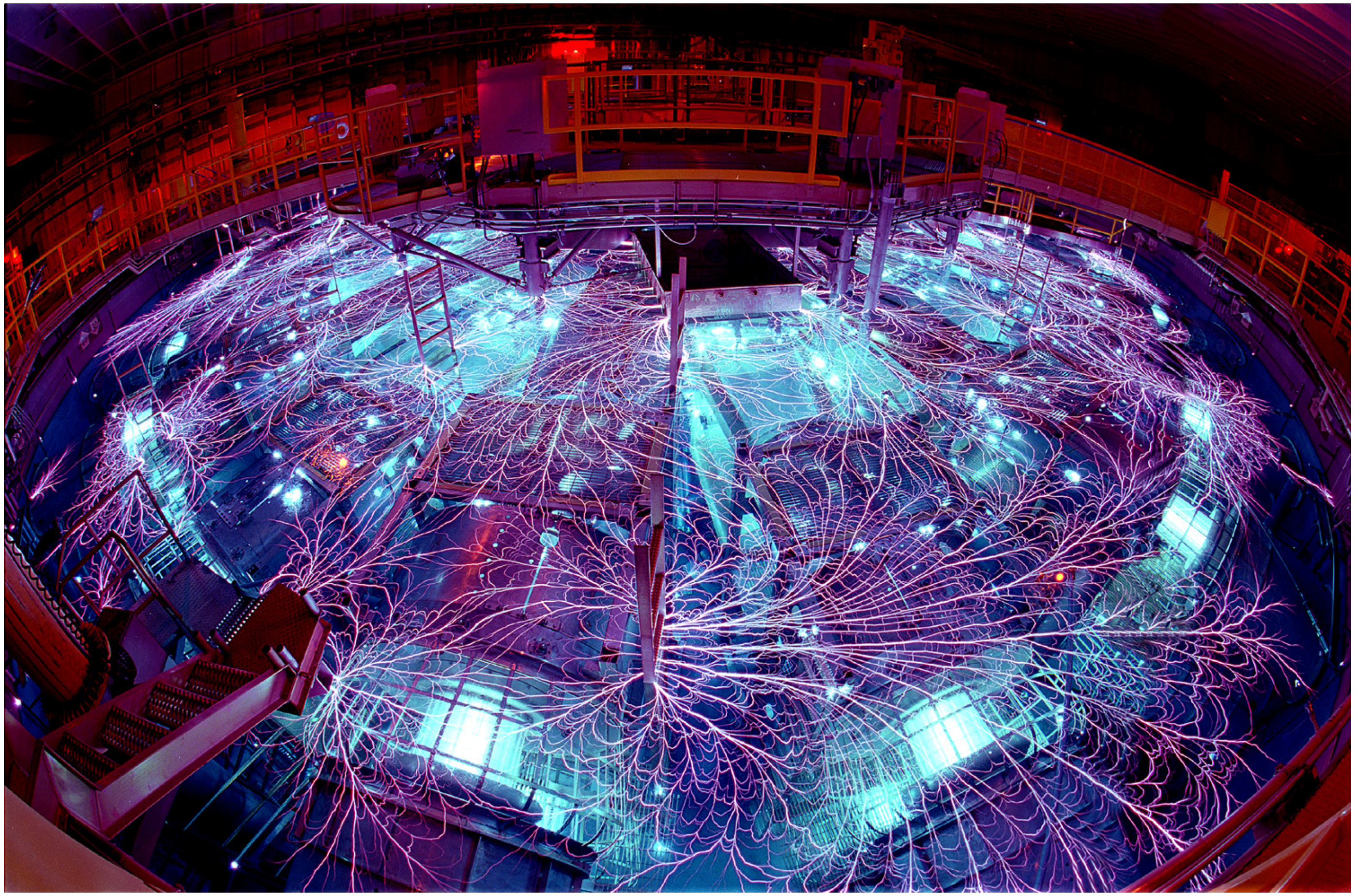
Dielectric Oils (cont.)

- Silicon oils
  - High quality
  - Expensive
- Vegetable oils: castor, rapeseed, canola, etc.
  - Increased usage
  - Low toxicity/environmental impact/high flash point
  - 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

Water as Dielectric

- Water and Ethylene Glycol are often used in pulse forming lines 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
    - $RC = \rho\varepsilon \sim 2$ µs maximum for water at 20° 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, $\alpha\ t^{0.33-0.5}$ (see Pulsed Power Formulary)
    - Typical pulsed operation: ~ 50 – 200 kV/cm (~half the strength of oil)

Bulk Breakdown Field Exceeds Surface Flashover Field: SNL Z-machine



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 with a uniform field
  - $E_{BD} \approx 25p + 6.7(p/d)^{½}$ (kV/cm)
    - Gas pressure, p (atm absolute)
    - Conductor spacing, d (cm)
  - Relative breakdown strength of gases at standard temperature and pressure:
    - Air & Nitrogen 1.0
    - SF_6 2.7
    - H_2 0.5
    - 30% SF_6, 70% Air 2.0
    - Noble Gasses < 1

Dielectric Geometry

- Local electric field exceeding dielectric strength limit starts breakdown
  - Mainly for liquid and gaseous dielectrics
  - Use an approximate geometry to estimate maximum electric field
  - Compare to dielectric strength of media as first check

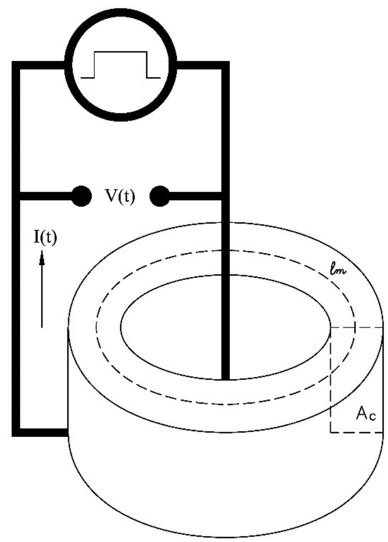
CONFIGURATION	FORMULA FOR E_{max}	EXAMPLE
Two parallel plane plates	$\frac{U}{a}$	U = 100 kV, a = 2 cm, E = 50 kV/cm.
Two concentric spheres	$\frac{U}{a} \cdot \frac{r+a}{r}$	U = 150 kV, r = 3 cm, a = 2 cm, E = 125 kV/cm.
Sphere and plane plate	$0.9 \frac{U}{a} \cdot \frac{r+a}{r}$	U = 200 kV, r = 5 cm, a = 8 cm, E = 58.5 kV/cm.
Two spheres at a distance a from each other	$0.9 \frac{U}{a} \cdot \frac{r+a/2}{r}$	U = 200 kV, r = 5 cm, a = 12 cm, E = 33 kV/cm.
Two coaxial cylinders	$\frac{U}{2.3\, r \lg \frac{r+a}{r}}$	U = 100 kV, r = 5 cm, a = 7 cm, E = 22.9 kV/cm.
Cylinder parallel to plane plate	$0.9 \frac{U}{2.3\, r \lg \frac{r+a}{r}}$	U = 200 kV, r = 5 cm, a = 10 cm, E = 32.8 kV/cm.

CONFIGURATION	FORMULA FOR E_{max}	EXAMPLE
Two parallel cylinders	$0.9 \frac{U/2}{2.3\, r \lg \frac{r+a/2}{r}}$	U = 150 kV, r = 6 cm, a = 20 cm, E = 11.5 kV/cm.
Two perpendicular cylinders	$0.9 \frac{U/2}{2.3\, r \lg \frac{r+a/2}{r}}$	U = 200 kV, r = 10 cm, a = 10 cm, E = 22.2 kV/cm.
Hemisphere on one of two parallel plane plates	$\frac{3U}{a}$; $(a >> r)$	U = 100 kV, a = 10 cm, E = 30 kV/cm.
Semicylinder on one of two parallel plane plates	$\frac{2U}{a}$; $(a >> r)$	U = 200 kV, a = 12 cm, E = 33.3 kV/cm.
Two dielectrics between plane plates ($a_1 > a_2$)	$\frac{U \epsilon_1}{a_1\epsilon_2 + a_2\epsilon_1}$	U = 200 kV, ϵ_1 = 2, ϵ_2 = 4, a_1 = 6 cm, a_2 = 5 cm, E = 11.8 kV/cm.

Fig. 6-5. Maximum field strength, E, with a potential difference, U, between the electrodes for different electrode configurations. (A. Bouwers and P.G. Cath, "The Maximum Electrical Field Strength for Several Simple Electrode Configurations," Philips Technical Review, Vol. 6, No. 9, with permission.)

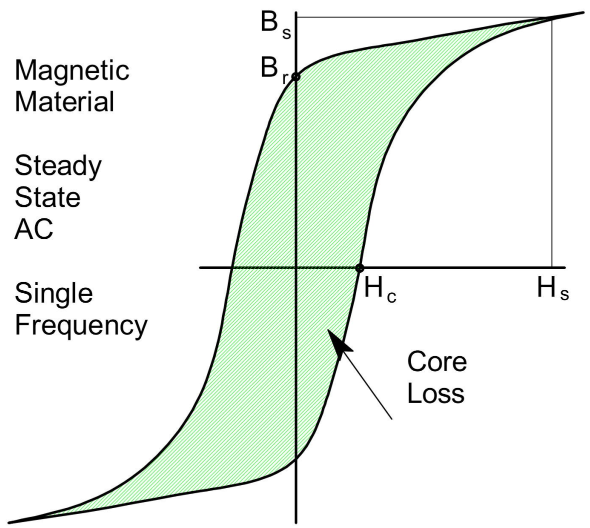
Magnetic Material Properties

- Faraday's law
  - $V = -d/dt \int \mathbf{B} \bullet d\mathbf{A}$
  - $V \boldsymbol{\tau} = -\Delta B \, A_c \, N$
    - Cross sectional area of core, A_c
    - Pulse voltage, V
    - Pulse duration, $\boldsymbol{\tau}$
- Ampere's law
  - $\int \mathbf{B} \bullet d\boldsymbol{\ell} = \mu I$
  - Define quantity $H=B/\mu \Rightarrow \int \mathbf{H} \bullet d\boldsymbol{\ell} = N\,I$
  - $H = N\,I/\ell_m$
    - Magnetizing current, I



Magnetic Material Properties (cont.)

- Permeability, μ
  - $\mu(H/m) = B(T)/H(A/m)$
  - H only depends on applied current and geometry, not material.
  - Permeability of free space, $\mu_o = 4\pi \text{ X } 10^{-7}$ H/m
  - Relative permeability, $\mu_r = \mu/\mu_o = B(G)/H(Oe)$
    - $\mu_r \approx 25{,}000$ for Fe,
    - $\mu_r \approx 400$ for Carbon steel
- Hysteresis loop
  - Plot of B vs H
  - Slope is incremental μ
  - Chord is pulse μ
  - Area is energy loss
- Flux swing, ΔB
  - Change in flux density to saturate ($\mu \rightarrow \mu_o$)
  - Typically remnant flux (H=0), B_r, to saturation flux, B_s: $\Delta B = B_r + B_s$



Magnetic Materials

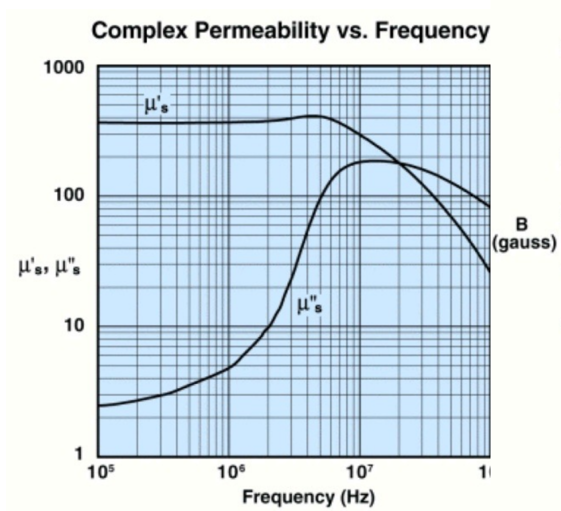
- Two types of material are typically used
  - Ferrimagnetic materials: ferrite cores
    - μ_r: ~500 – 2000 (typical)
    - μ_r approximately constant to >MHz for some formulations
    - ρ: ~10^9 Ω•cm
    - ΔB: ~0.5 T
  - Ferromagnetic materials: “steel” tape-wound cores
    - ρ: ~10^{-5} Ω•cm
    - Eddy currents impede field penetration into material (skin effect)
    - Must be wound from thin (pulse width dependent) ribbon interleaved with insulator or insulating layer on material
    - Insulator does not have magnetic properties, effective area of magnetic material reduced by packing factor, η = insulator thickness/total thickness
    - 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

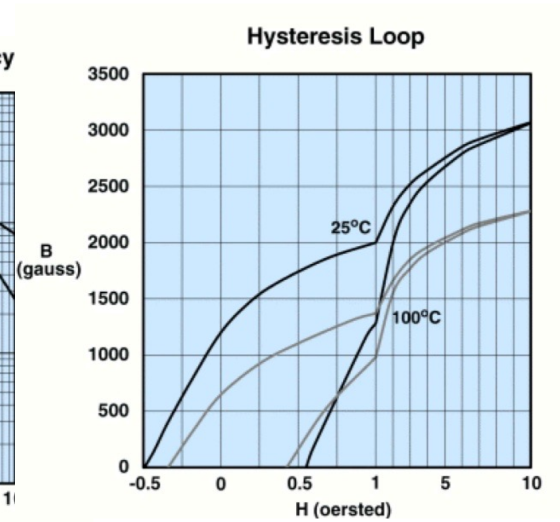
Ferrite

- Two dominant compositions
  - NiZn
    - Highest frequency response
    - High frequency transformers & chokes, magnetic switching, induction accelerator cores
    - CN20, CMD5005, PE-11B
  - Plot Example: Fair-Rite 51
    - Low-loss
    - Modest frequency response (5 MHz)
    - Not “square” hysterias loop

$$\tan\delta_m = \frac{R_s}{\omega L_s} = \frac{\mu''_s}{\mu'_s}$$

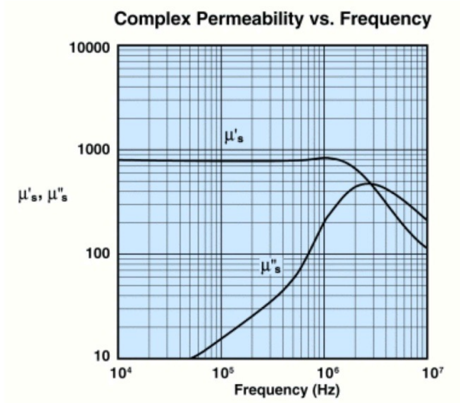
1 T = 10,000 G

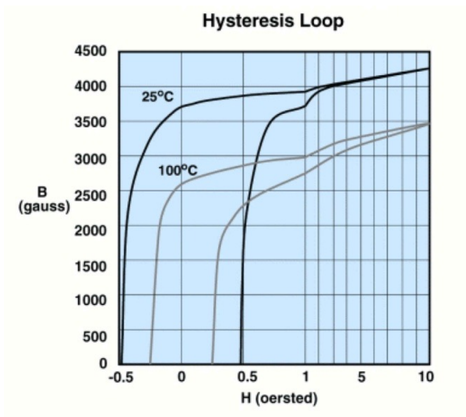




Ferrite

- Second dominant composition
  - MnZn
    - Larger ΔB, but lower frequency.
    - Switch-mode power supply transformers
    - Plot Example: Fair-Rite 85
      - ‘Square’ loop





Tape Wound Core Materials

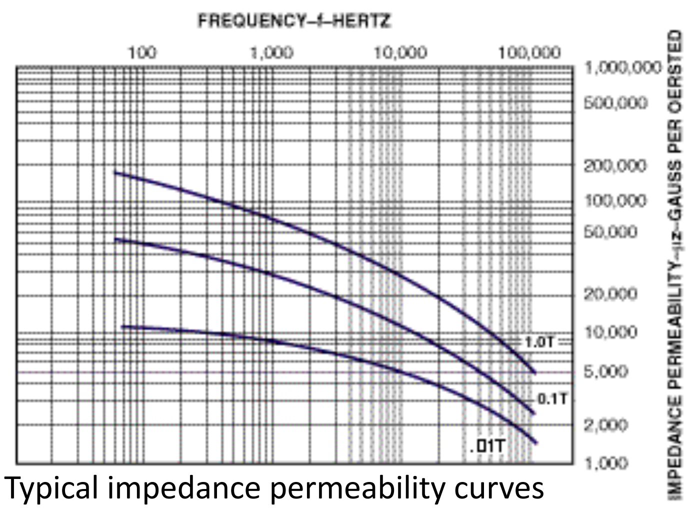
- Crystalline
  - Traditional core material
  - Common formulations: Si-Fe and Ni-Fe
  - Lowest cost
  - Poorest high frequency performance
- Amorphous (Metglas ©)
  - Developed in 70's/80's
  - Iron-based, Ni-Fe-based, and cobalt-based formulations
  - Low loss
  - Higher frequency response
  - Magnetic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

Crystalline Materials

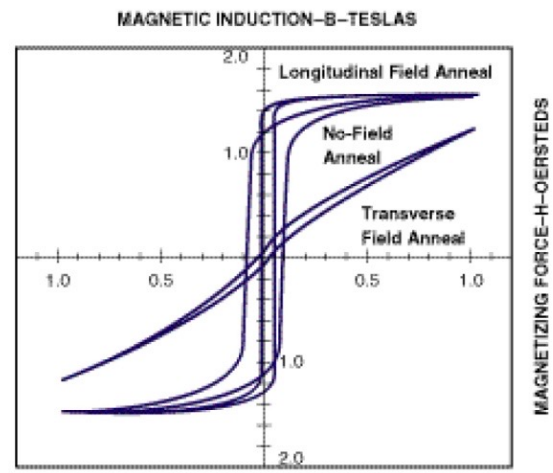
- Si-Fe
  - $\Delta B > 3$ T
  - $\mu_{max} > 25{,}000$
  - Low frequency applications, 1 – 16 mil thickness
- Ni-Fe
  - $\Delta B \sim 1.5$ T
  - $\mu max > 25{,}000$ (>100,000 grain oriented material)
  - Thin material, <1 mil, good at higher frequencies, but expensive

Amorphous Materials

- 2605 SA1
  - Most common Fe-based material
  - Modest high frequency response
  - Lowest cost of the amorphous materials
  - ΔB ~ 3 T
  - μ_{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
  - µmax ~ 500,000 (dc)

Nano-crystaline Materials

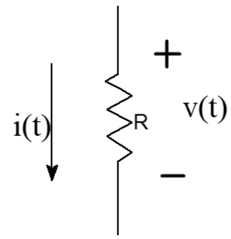
- Similar high frequency permeability and squareness as 2605CO
- $\Delta B \sim 2$ T
- $\mu_{max} \sim 60{,}000$
- Lower value of negative H needed to reset core.
- Major suppliers
  - Hitachi “Finemet”
  - Vacuumschmelze
- Hitachi makes excellent cores (including toroids)
  - Well annealed
  - Well constructed (ceramic insulation)

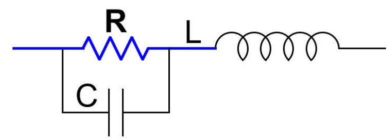
Passive Components and Devices

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

Resistors

- Resistor behavior





- $v(t) = R\, i(t)$
- $E = \int v\, i\, dt$
- $\Delta T = \dfrac{E}{m\, C_m}$
  - C_m is the specific heat of the material (J/kg/C)
  - m is the mass of the material (kg)
  - E is the energy deposited (J)
  - Assuming no loss of heat to surroundings
  - Applies to any thermal mass

High-Frequency Equivalent Circuit

ESL ≡ parasitic inductance

Capacitance for high value resistors usually more about structure resistor is in than inherent

Inductance for low value resistors usually more about structure around resistor than structure of resistor

Losses in metal resistance

Resistor Types

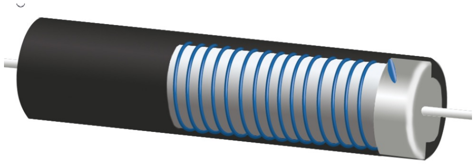
[1] https://www.photonics.com/images/Web/Articles/2003/7/1/SpectraPhysics_Figure1_Horz.jpg 1-9-2022

[2] fundemental-construction-of-wirewound-resistors.jpg (1266 × 488) (riedon.com) 1-9-2022

- 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

[1]

- 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



[2]

Resistor Types (cont.)

- Composition
  - Large active material mass → large energy handling capacity
  - Carbon Composition
    - 2W "standard" no longer manufactured, but see also ceramic composition
    - Voltage and power capacity varies by value
      - 2W: ~80 J, >2 kV repetitive, ~10 kV non-repetitive
  - Ceramic Composition
    - Ohmite OX/OY series
    - HVP APC RT/RL and C Series
    - Even better than carbon comps
    - 2W: ~20 kV non-repetitive
  - Bulk ceramic
    - Carborundum → Cesiwid → Kanthal Globar →Now product line owned by Ohmite
    - HVR sells custom clamped assemblies, also Asian and European manufacturers
    - Vary composition for high voltage, high average power, and high peak power
    - Special coatings for immersion in oil (reduces 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
  - Vacuum diode: $I = \mu V^{1.5}$
  - High power but high cost

Component Manufacturer Websites

- Resistors
  - EBG Resistors: http://ebgusa.com/
  - RCD Components: http://data.rcdcomponents.com:8080/rcd/mobile/
  - HVR Advanced Power Components: http://www.hvrapc.com/
  - International Resistive Co.: http://www.ttelectronicsresistors.com/
  - Ohmite Tubular Ceramic Resistors: https://www.ohmite.com/tubular-ceramic-resistors/
  - Caddock Resistors: http://www.caddock.com/
  - Ohmite: http://www.ohmite.com/

Capacitors

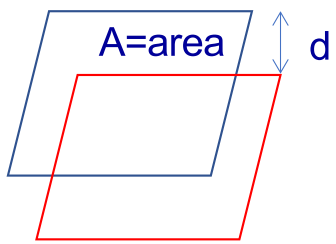
- Capacitor energy

$$Energy = \frac{1}{2}\varepsilon\times(E - field)^2\times Volume$$

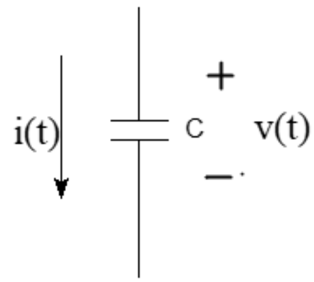
$C = \varepsilon\times A/d$ Capacitance of parallel plates

$$E - field = V/d$$

$$Energy = 1/2CV\hat{}2$$



- Capacitor behavior

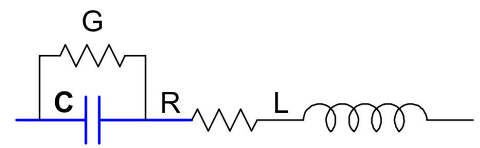


$$q(t) = C\,v(t)$$

$$i(t) = C\,\frac{dv(t)}{dt}$$

$$\Delta i = C\frac{\Delta v}{\Delta t}$$

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



High-Frequency Equivalent Circuit

ESR ≡ parasitic resistance
R and G contribute, but ω dependant
R conductor, G dielectric
ESL ≡ parasitic inductance
DF ≡ dissipation factor = (ESR)ωC

Losses in metal resistance and dielectric from high frequency changing voltage.

Average current must be zero for voltage to stay bounded

Capacitor Types

- Electrolytic
  - Lossy above ~kHz
  - Low voltage, <kV
  - Energy density: ~1 J/cm^3
  - Limited use in pulsed power, except slow circuits
  - Unipolar
- Mica
  - High quality
    - Stable
    - Low loss
  - Energy density: ~0.01 J/cm^3
  - Limited distribution above kV, usually made to order
- Coaxial cable
  - Often acts as capacitor if terminated in high impedance
  - $C = \tau/Z$ (transit time/impedance)

Capacitor Types (cont.)

- Water
  - High energy density ~0.1 J/cm^3 (@200 kV/cm)
  - High voltage, ~MV
  - Due to limited resistivity, only useful in short pulse applications
  - Not commercially available
- Ceramic
  - Available to 50 kV
  - High average current types are available
  - Energy density ~0.025 J/cm^3
  - Low Inductance
  - 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

Film Capacitor Construction: Dielectric Materials

- Paper (wicks “oil”)
- Polymers
  - Polyester (Mylar®)
  - Polypropylene, High Crystalline Polypropylene (HCPP) best
  - Hazy films wick “oil”
- Oil/fluid (see slides 11 & 12)
- Combinations of the above

Film Capacitor Construction: Conductors

- Foil
  - Aluminum typical (zinc for ac applications)
  - 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 kΩ/□

Film Capacitors Construction: Trade-Offs

- 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 - 10^5 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
    - Self-healing: C drops as metalization erodes, ΔC = 5% is end-of-life

Component Manufacturer Websites

- Capacitors (larger stored energy custom):
  - CDE (Cornell Dublier merged with NWL): http://www.cde.com/capacitors
  - Vishay Power Film (distributed through C&H Technology and Richardson Electronics)
  - TDK: https://product.tdk.com/en/products/capacitor/index.html
  - GA/Maxwell: http://www.ga.com/capacitors

    Hard part is finding someone who will talk to you in the bigger companies
- Capacitors (smaller stored energy, not so custom):
  - Electronic Concepts: http://www.ecicaps.com/
  - Novacap: http://www.knowlescapacitors.com/novacap
  - CSI: http://www.csicapacitors.com/
  - WIMA
  - Kyocera AVX

Inductors

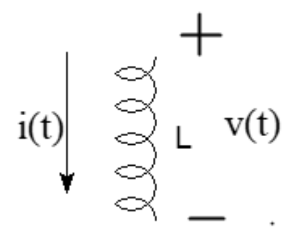
- Inductor Energy

$$Energy = \frac{1}{2\mu} \times (Bfield)^2 \times Volume$$

$$Energy = \frac{1}{2} L I^2$$

$$L = \frac{\mu N^2 A_C}{l_c}$$ Inductance of a core

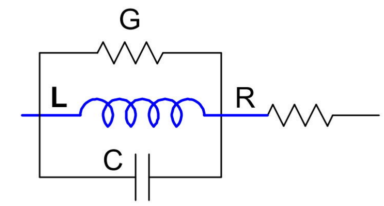
- Inductor behavior



$$\Phi(t) = L\, i(t) \,/\, N$$
$$\Lambda(t) = L\, i(t)$$

$$v(t) = L\, \frac{di(t)}{dt}$$
$$\Delta v = L \frac{\Delta i}{\Delta t}$$

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



High-Frequency Equivalent Circuit

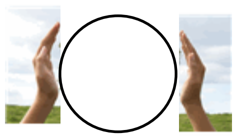
ESR ≡ parasitic resistance
  R and G contribute, but ω dependant
  R conductor losses, G core losses

Q ≡ quality factor = ωL/R or $\frac{E_{stored}}{E_{lost}}$

Losses in metal resistance and dielectric from high frequency changing voltage.

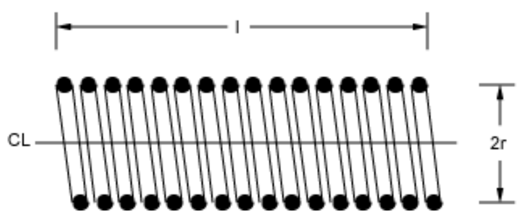
Average voltage must be zero for current to stay bounded

Inductor Types

- Current loop – Need a complete circuit
  - A few uH: 
  - 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)
- Coaxial cable
  - Often acts as inductor if terminated with a low impedance
  - L = τ Z (transit time • impedance)

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



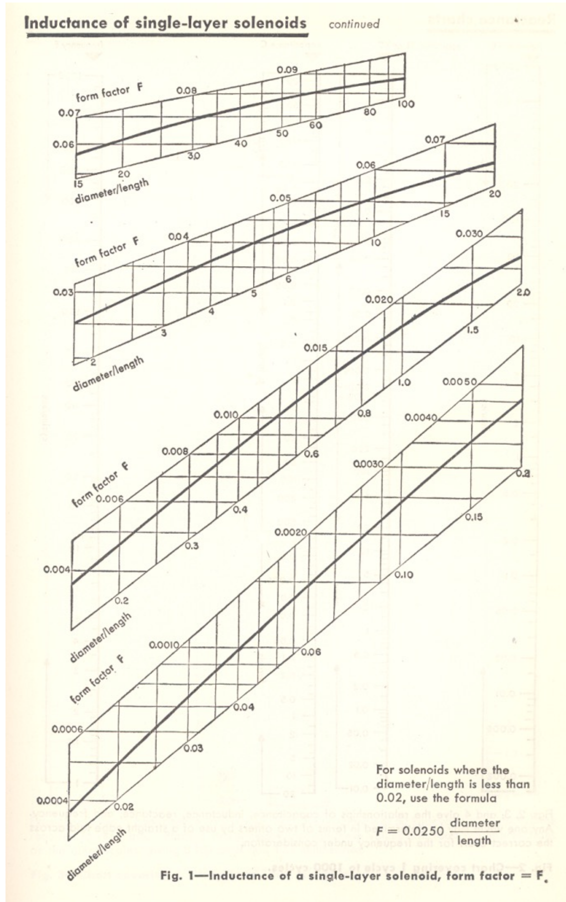
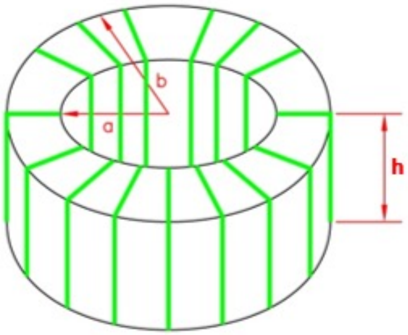


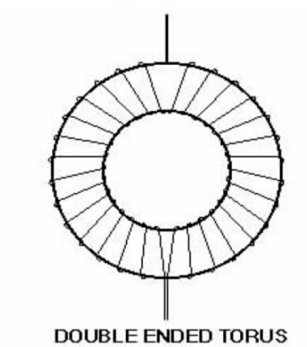
Fig. 1—Inductance of a single-layer solenoid, form factor = F.

F.J Mann (Ed), Reference Data for Radio Engineers, 3rd Ed, (1950).

Inductor Types

- Toroid
  - Closed field lines, minimize interaction with adjoining components
  - $L = (N^2 \mu h / 2\pi) \ln(b/a)$ (H) [rectangular core]
    - N turns
    - Toroid outer radius, b (m)
    - Toroid inner radius, a (m)
    - Toroid thickness, h (m)
  - Double ended for HV
    - Better voltage grading around toroid
    - Lower stray capacitance than continuous wound





Component Manufacturers

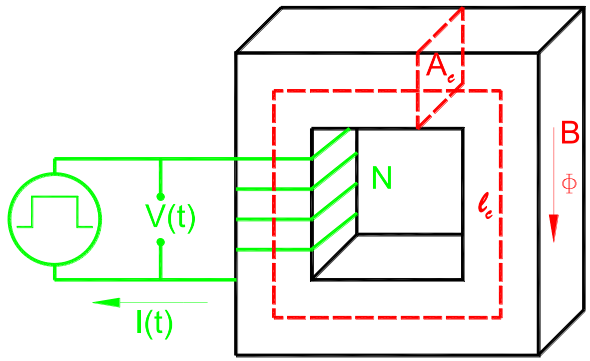
- Most commercial inductors are made to order
- Specialty companies with experience in high voltage or high current or pulsed operation (not necessarily all)
  - Stangenes Industries (CA)
  - E Craftsmen (ON)
  - Vellatron (was Smallwood) (ON)
  - Hammond Power Solutions (ON)
  - Spang Power (outsources) (PA)
  - Neeltran (CT)
- Some smaller inductor companies
  - Shape LLC (IL)
  - Custom Coil (CA)
  - Triad Magnetics (CA)

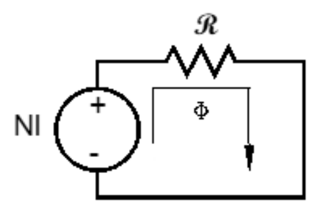
Increasing Inductance with a High Permeability Core

- Air core: $\mu = \mu_o$
    - Constant, independent of frequency and current (subject to parasitic effects)
    - Low permeability
- "Cored" (i.e. filled with magnetic material): $\mu = \mu_o \, \mu_r$
    - μ_r as high as $>10^5$
    - $\mu = f$ (frequency, drive amplitude, temperature)
    - V $\boldsymbol{\tau}$ constraint (saturation)
- Compromise: gapped core
    - Still saturates, stores more energy that cored alone

Magnetic Circuit

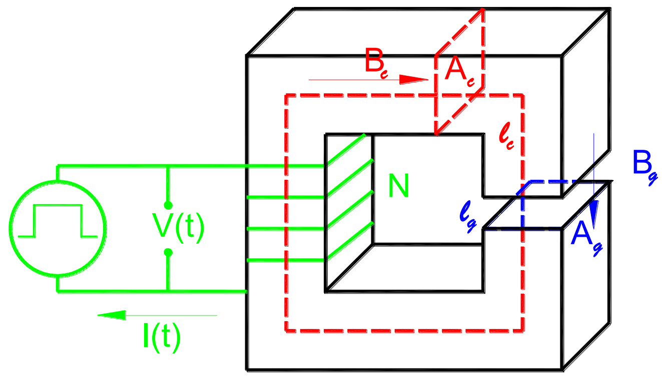
- Magnetic flux, Φ, flows along a continuous path around core
- Flux is driven by magneto-motive force, NI
- Flux is opposed by the circuit reluctance, $\mathcal{R} = l/\mu A$
- Analogy to electrical circuit
  - $\Phi \leftrightarrow I$
  - $NI \leftrightarrow V$
  - $\mathcal{R} \leftrightarrow R$
    - Series & parallel similarly
  - $NI = \Phi\mathcal{R} = \Phi l/\mu A$





Gapped Core Inductor

- From Ampere's law
  - $NI = H_c l_c + H_g l_g$
- Flux continuity
  - $\Phi = B_c A_c = B_g A_g$
- Since $B = \mu H$
  - $H_c = \frac{\Phi}{\mu_c A_c}, H_g = \frac{\Phi}{\mu_g A_g}$
  - $NI = \Phi \left[\frac{l_c}{\mu_c A_c} + \frac{l_g}{\mu_g A_g} \right]$
- Since $N\Phi = LI$
  - $L = \frac{N^2}{\left[\frac{l_c}{\mu_c A_c} + \frac{l_g}{\mu_g A_g} \right]}$

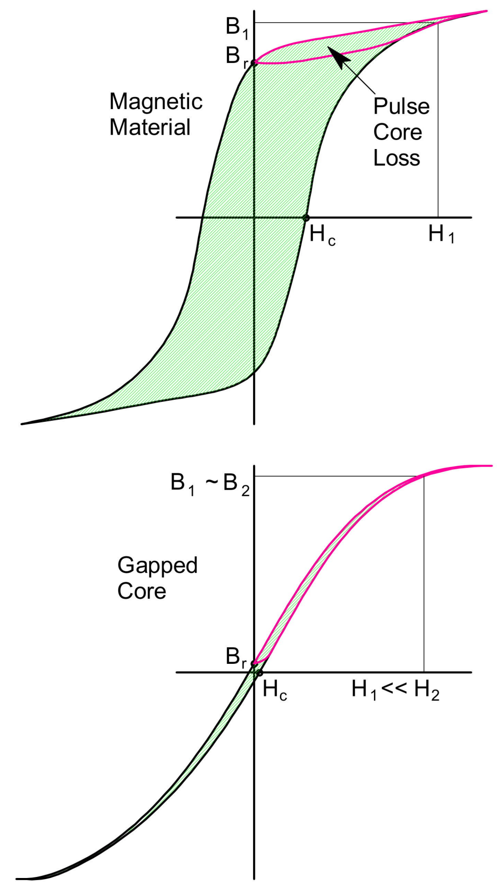


Impacts of Gapping Inductor Core

- Total reluctance, $\mathcal{R} = \frac{l_c}{\mu_c A_c} + \frac{l_g}{\mu_g A_g}$
- Compare: $\frac{l_c}{\mu_c A_c}$ to $\frac{l_g}{\mu_g A_g}$
  - $A_c \approx A_g$, $\mu_c/\mu_g \sim 10^4$, $l_c/l_g \sim 10^2$
  - $\frac{l_c}{\mu_c A_c} << \frac{l_g}{\mu_g A_g}$
- Therefore
  - $\mathcal{R} \approx \frac{l_g}{\mu_g A_g}$
  - $L \approx \frac{\mu_g A_g N^2}{l_g} = N^2/\mathcal{R}$
  - Inductance is decreased when the core is gapped
  - Inductance is virtually independent of μ_c
  - Inductor can store much more energy (energy mostly in gap)

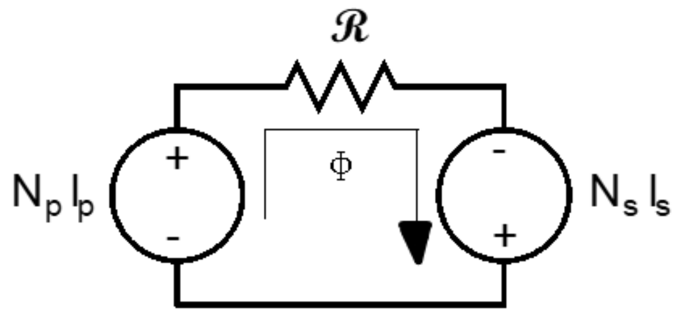
Impact of Gapping Core

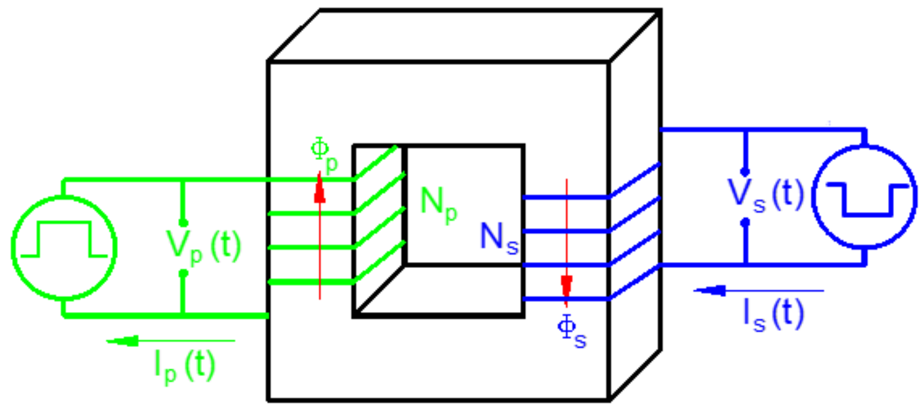
- Using magnetic material to make an inductor or transformer
  - Unipolar Pulsing
    - Addition of small air gap to reduce remnant field in core
  - Flux swing, ΔB, can be increased at cost of lower inductance
- Reset magnetic field in core
  - If don't naturally reset field it or if don't have gap in core
  - To reduce core size by getting more ΔB



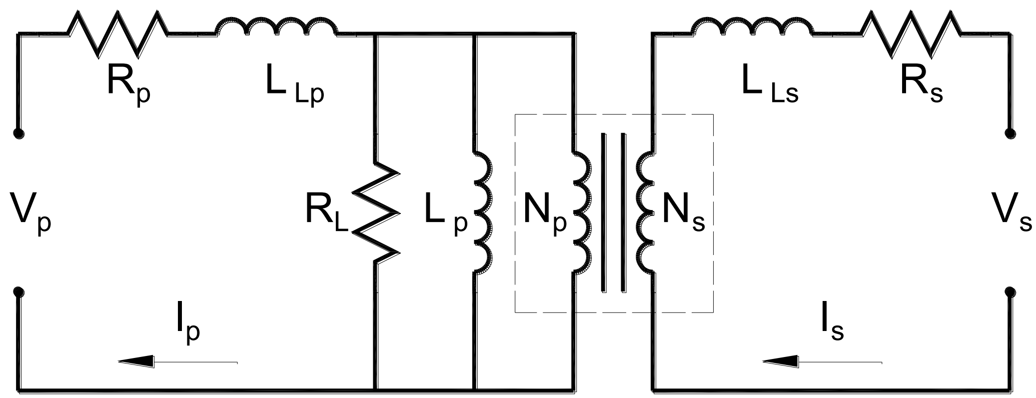
Coupled Inductors & Transformers

- Add a second winding to inductor
- By super-position, flux adds
  - $\Phi\mathcal{R} = N_p I_p + N_s I_s$
- "Ideal" transformer
  - $\mu_c \rightarrow \infty$
  - $\mathcal{R} \rightarrow 0$
  - $N_p I_p + N_s I_s = 0$
- Faraday's law
  - $-\frac{d}{dt}\Phi = \left(\frac{V}{N}\right)_p = \left(\frac{V}{N}\right)_s$
  - $\frac{V_p}{N_p} = \frac{V_s}{N_s}$





Transformer Model



Ideal transformer

- Ideal transformer identities
  - $V_s/V_p = N$
  - $I_p/I_s = N$
  - $Z_s/Z_p = N^2$

- Loss terms
  - Primary winding: Rp
  - Secondary winding: Rs
  - Equivalent core loss: RL

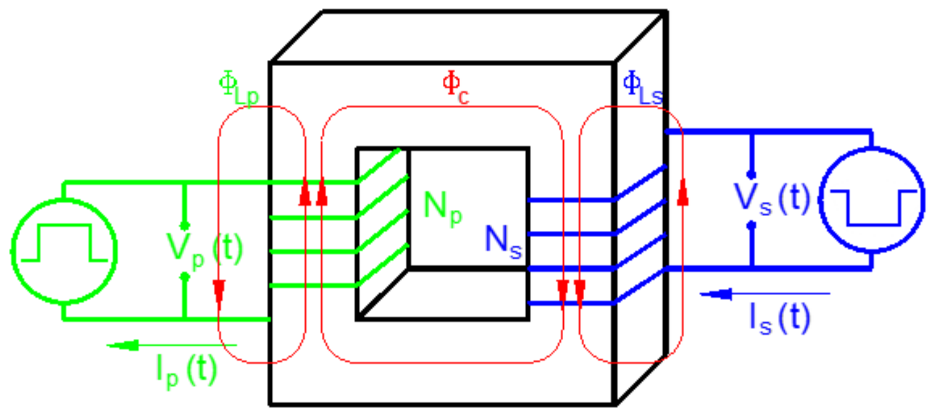
- Inductance terms
  - Primary leakage: L_{Lp}
  - Secondary leakage: L_{Ls}
  - Primary (magnetization): L_p

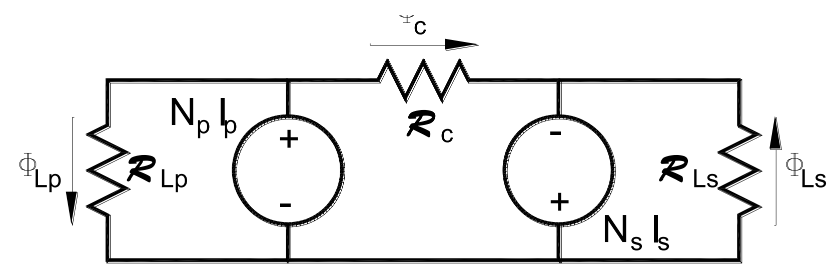
- Winding turns
  - Primary: N_p
  - Secondary: N_s
  - Ratio: $N = N_s/N_p$

Apply Circuit Analogy to Transformer Model

- Noting: $\Phi = NI/\mathcal{R}$ and $L = N^2/\mathcal{R}$
  - $\Phi_{Lp} = \frac{N_p I_p}{R_{Lp}}$ R here is reluctance
  - $\Phi_{Ls} = \frac{N_s I_s}{R_{Ls}}$
  - $\Phi_c = \frac{N_p I_p + N_s I_s}{R_c}$
  - $L_{Lp} = \frac{N_p^{\ 2}}{R_{Lp}}$
  - $L_{Ls} = \frac{N_s^{\ 2}}{R_{Ls}}$
  - $L_c = \frac{N_p^{\ 2}}{R_c}$ (primary referenced)

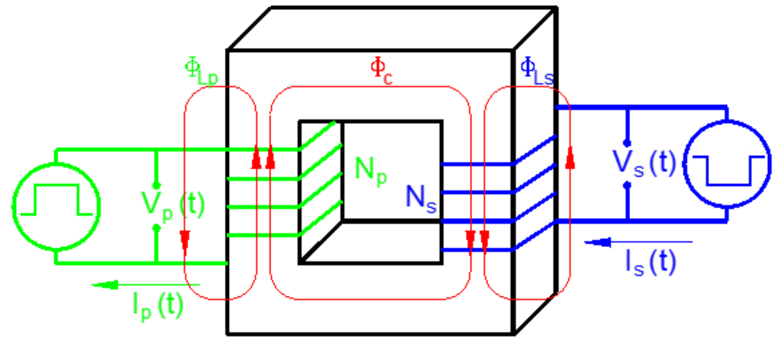
$remember, N\Phi = LI$



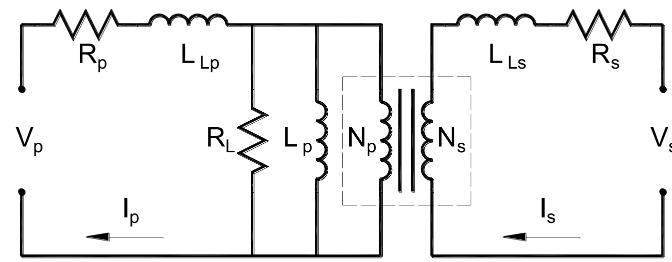


Apply Circuit Analogy to Transformer Model

- Introduce flux linkage
  - $\lambda = N\Phi$ (flux linked by N-turn loop, $V = \frac{d\lambda}{dt}$)
  - $\lambda_p = Np(\Phi_c + \Phi_{Lp}) = \frac{{N_p}^2}{R_c} I_p + \frac{{N_p}^2}{R_{Lp}} I_p + \frac{N_p N_s}{R_c} I_s$
  - $\lambda_s = Ns(\Phi_c + \Phi_{Ls}) = \frac{{N_s}^2}{R_c} I_s + \frac{{N_s}^2}{R_{Ls}} I_s + \frac{N_p N_s}{R_c} I_p$

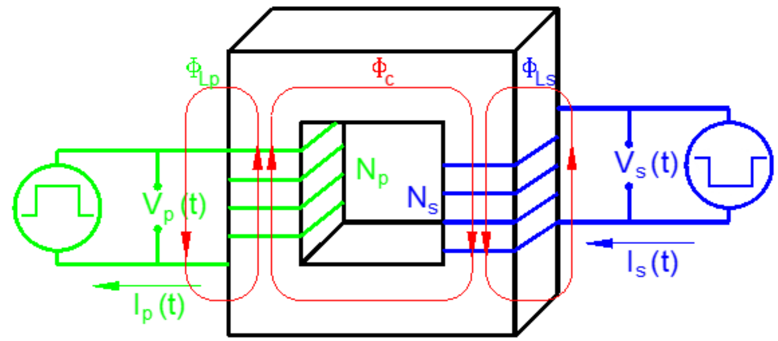


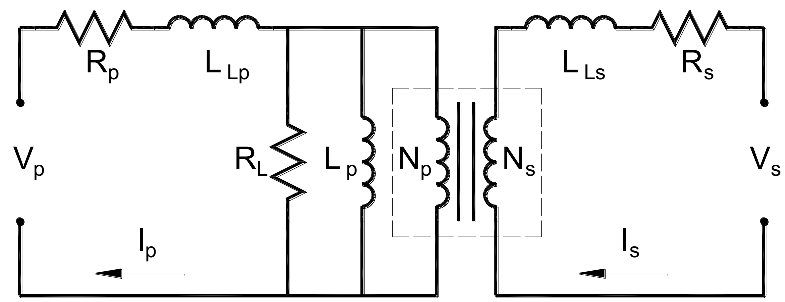
- Two-port inductance matrix
  - $\begin{bmatrix} \lambda_p \\ \lambda_s \end{bmatrix} = \begin{bmatrix} \frac{{N_p}^2}{R_c} + \frac{{N_p}^2}{R_{Lp}} & \frac{N_p N_s}{R_c} \\ \frac{N_p N_s}{R_c} & \frac{{N_s}^2}{R_c} + \frac{{N_s}^2}{R_{Ls}} \end{bmatrix} \begin{bmatrix} I_p \\ I_s \end{bmatrix} = \begin{bmatrix} L_{11} & L_M \\ L_M & L_{22} \end{bmatrix} \begin{bmatrix} I_p \\ I_s \end{bmatrix}$
  - $\begin{bmatrix} V_p \\ V_s \end{bmatrix} = \begin{bmatrix} L_{11} & L_M \\ L_M & L_{22} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} I_p \\ I_s \end{bmatrix}$
  - Where $L_{11} = L_{Lp} + L_c, \quad L_M = \frac{N_s}{N_p} L_c, \quad L_{22} = L_{Ls} + \left(\frac{N_s}{N_p}\right)^2 L_c$



Apply Circuit Analogy to Transformer Model

- Magnetizing (primary) inductance
  - $L_p = Lc = \frac{N_p}{N_s} L_M$
- Leakage inductances
  - Primary: $L_{Lp} = L_{11} - \frac{N_p}{N_s} L_M$
  - Secondary: $L_{Ls} = L_{22} - \frac{N_s}{N_p} L_M$
- Effective turns ratio
  - $n_e = \sqrt{\frac{L_{22}}{L_{11}}}$
- Coupling coefficient
  - $k = \frac{L_M}{\sqrt{L_{11} L_{22}}}$

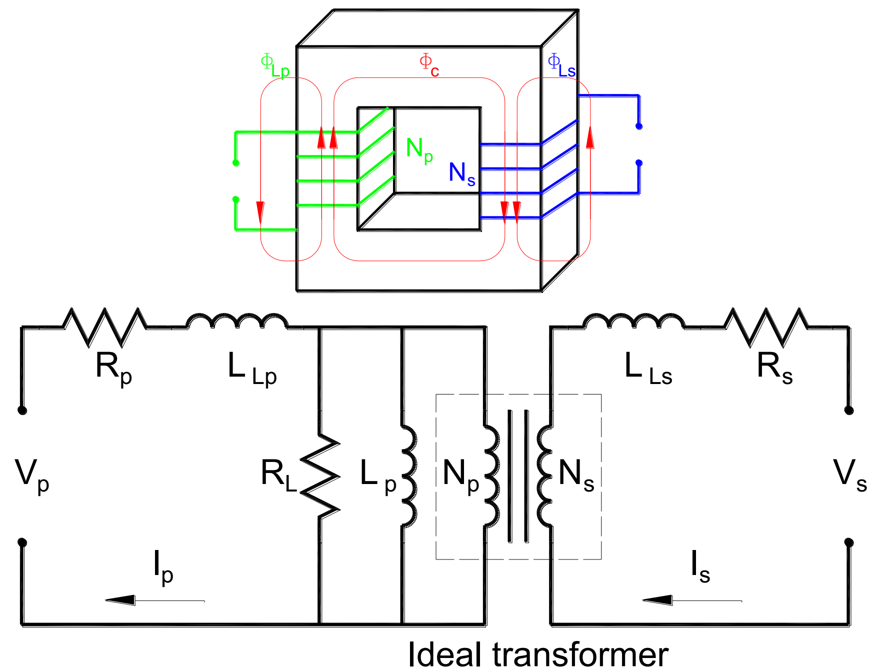




Ideal transformer

Transformer Model: Practical Interpretation

- Primary (magnetizing) inductance
  - Open secondary, measure across primary
    - $L = L_p + L_{Lp}$
    - $L_p >> L_{Lp}$, measure ~ L_p
  - Open primary, measure across secondary
    - $L = N^2 L_p + L_{Ls}$ (translate L to 2[nd]ary reference)
    - $N^2 L_p >> L_{Ls}$, measure ~$N^2 L_p$
- Leakage inductance
  - Short secondary, measure across primary
    - $L = L_{Lp} + \frac{L_{Ls}}{N^2}$
    - Isolation transformer, N=1, $L_{Lp} \approx L_{Ls}$
    - HV step-up transformer, $L_{Lp} << L_{Ls}$ due to HV insulation on 2[nd]ary
    - $L_{Lp} = (1-k)L_{11} \approx$ (1-k)Lp   Remember, $L_{11} = L_{Lp} + L_p$



Transformer Applications

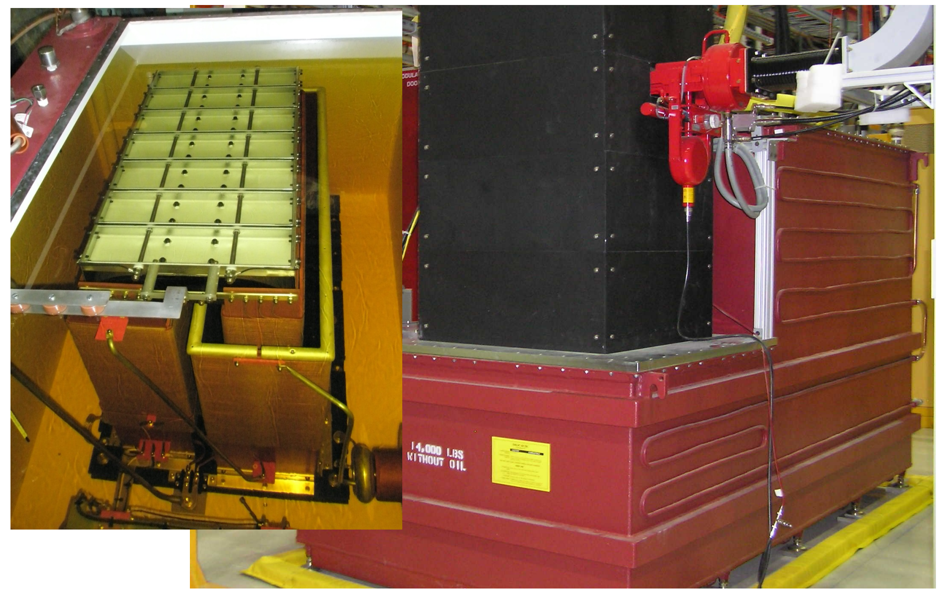
- Voltage/current scaling
  - Generally high voltage generation from a lower voltage source
  - Matching switching device characteristics to load characteristics
- Impedance matching from one transmission line to another
  - Few $\Omega < Z_{TL} <$ ~100 Ω
- Isolation
  - Floating ground
  - Block dc signal component

Transformer Types

- AC
  - 60 Hz
  - Step-up (neon sign), step-down (filament), isolation
  - Decrease in size with increasing frequency
- Pulse
  - Uni-polar
  - Ubiquitous in low duty factor HV applications
- ~~DC~~
  - Faraday's law, $\int V dt = NA \int dB$
  - $\int_0^\infty V dt \to \infty$ for DC, therefore, $NA\Delta B \to \infty$
  - Transformers get big as the frequency goes down

Pulse Transformers

- Functions
  - Voltage gain
  - Impedance matching
  - Teach humility
- Commercial pulse transformers are generally made to order



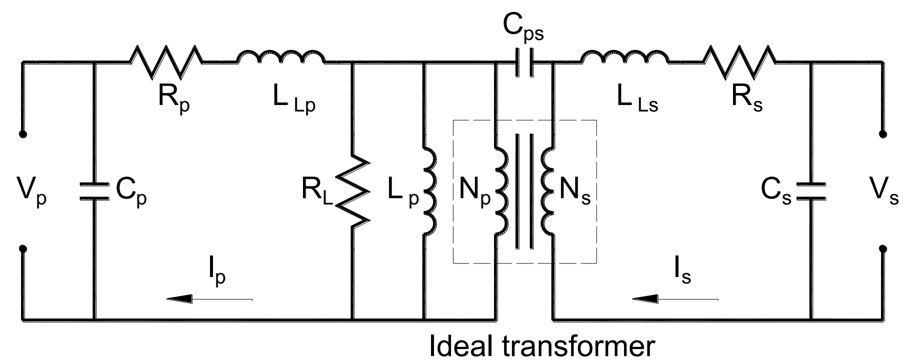
^ 1500 μs pulse length

Stangenes Industries klystron transformers

<- few μs pulse length

Transformers: Practical Limitations

- Core
  - Material limitations
    - Vτ constraint
    - $\mu = f(\omega, I, \text{temperature})$
  - Typically gapped
- Primary inductance
  - $\tau_{droop} = L/R$
- Stray capacitance
  - Primary to secondary
    - In series with leakage inductance
    - Operate below self-resonance
  - Secondary inter-winding
    - Load secondary



Transmission Lines (TL)

- Transverse Electric and Magnetic (TEM) modes propagate over very large frequency range

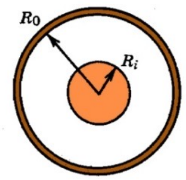
- A transmission line consists of two or more conductors with a uniform cross section for the propagation of electromagnetic energy, guides energy
  - Coaxial
  - Planar or Two Wire
- Impedance
  - Z = $\sqrt{\frac{L}{C}}$
- Propagation velocity
  - v = $\frac{1}{\sqrt{\epsilon\,\mu}} = \frac{c}{\sqrt{\epsilon_r \mu_r}} = \frac{1}{\sqrt{L\,C}}$
- Propagation time for a line of length l
  - $\tau = \frac{l}{v} = \sqrt{L\,C}$ where L and C are total for length of line
- Losses complicate all of these formulae and introduce frequency dependence

Common Transmission Line Geometries

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

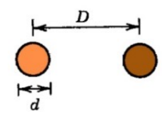
1 Coaxial transmission line:

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



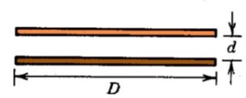
2 Two-wire transmission line

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



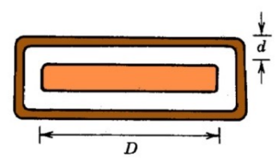
3 Isolated parallel plates ($d \ll D$)

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



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).

from “Principles of Charged Particle Acceleration,” S. Humphries, Jr.

Discrete Element Transmission Line Approximation

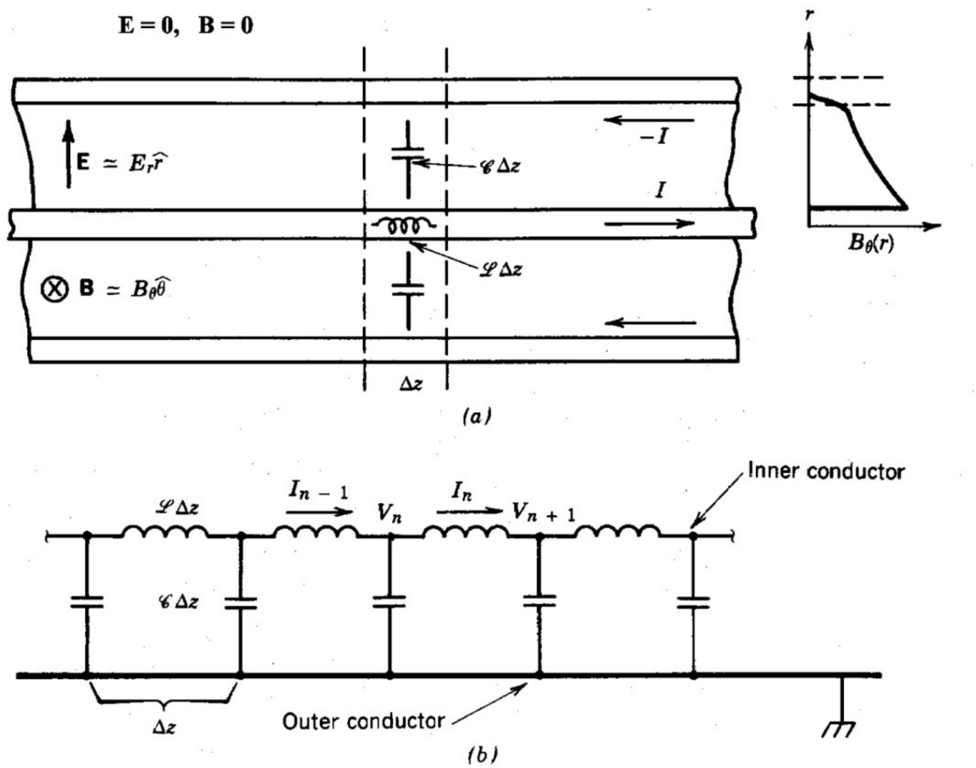
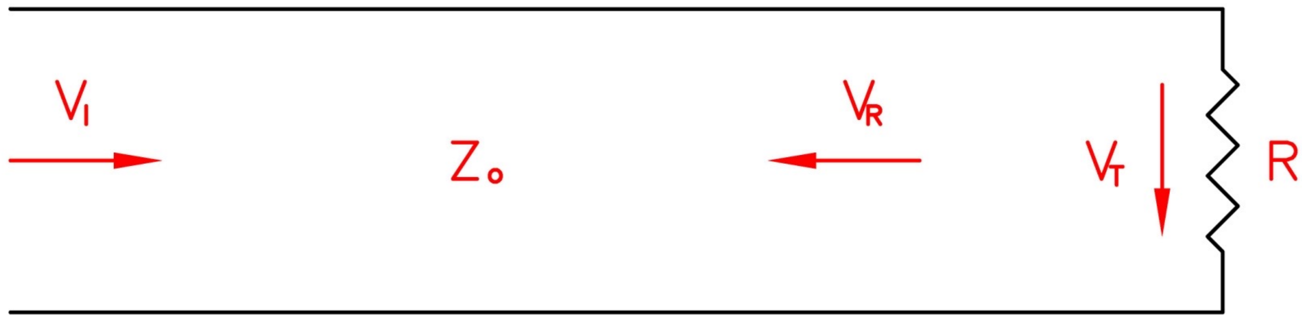


Figure 9.29 Coaxial transmission line. (*a*) Physical basis for lumped circuit element model of TEM wave propagation. (*b*) Lumped circuit element analog of a coaxial transmission line.

from, "Principles of Charged Particle Acceleration," S. Humphries, Jr.

Transmission Line Terminations

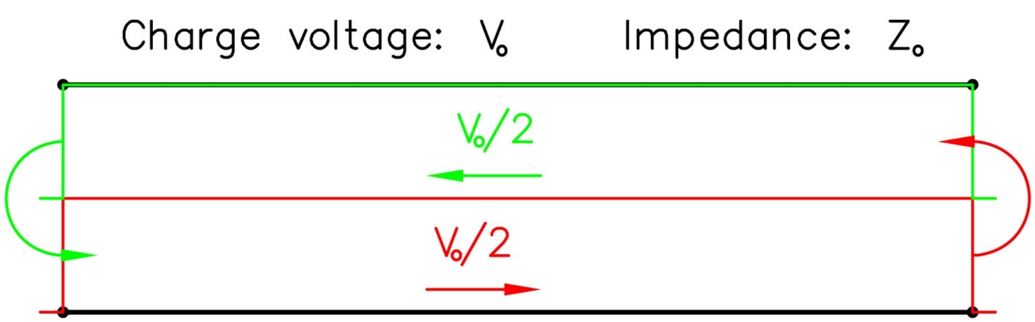


- Matched: $R = Z_O$, $V_T = V_I$, $V_R = 0$
- Open: $R = \infty$, $V_R = V_I$, $V_T = 2V_I$
- Short: $R = 0$, $V_R = -V_I$, $V_T = 0$
- General
  - Reflection coefficient $\Gamma = \frac{R-Z_O}{R+Z_O}$
  - Transmission coefficient $\mathrm{T} = \frac{2R}{R+Z_O}$
  - $\mathrm{T} - \Gamma = 1$
  - $V_T = \mathrm{T}V_I$
  - $I_T = V_T/R = \mathrm{T}V_I/R$
  - $V_R = \Gamma V_I$
  - $I_R = V_R/Z_o = \Gamma V_I/Z_o$

- 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
- $I_I = I_T + I_R$

Wave Model of Voltage Charged Transmission Line

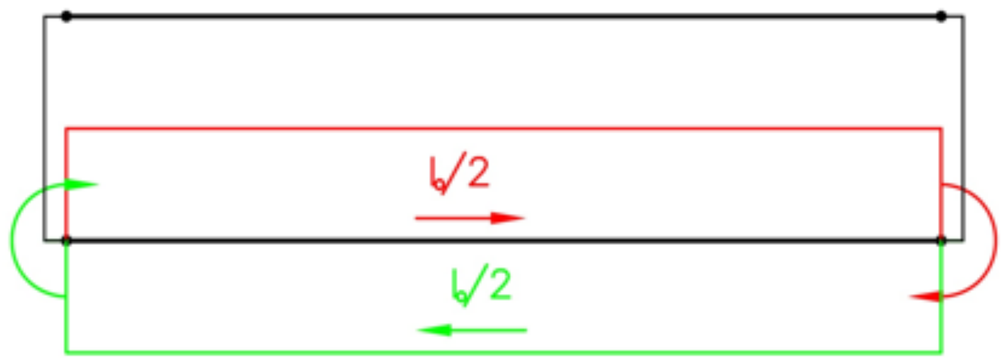
- Section of transmission charged to voltage, V_o, “open” at both ends
- Equivalent model
  - Propagating wave of voltage $V_o/2$ traveling left to right
  - Encounters open at end of line and reflects, same polarity and equal magnitude
  - Sum of left and right going waves is V_o
  - When left to right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



Charge voltage: V_o
Impedance: Z_o

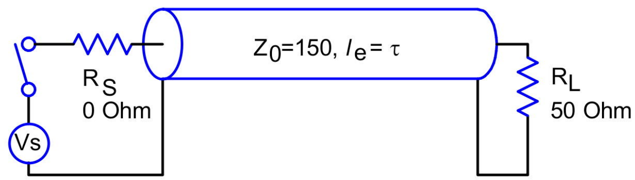
Wave Model of Current Charged Transmission Line

- 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, $I_T = I_l = I_o/2$ and $V_T = I_o Z_o/2$



Charge current: I_o
Impedance: Z_o

Analysis of TL Step Response: Bounce Diagrams



$$\Gamma_R = \frac{50 - 150}{50 + 150} = -\frac{1}{2}$$

$$\Gamma_L = \frac{0 - 150}{0 + 150} = -1$$

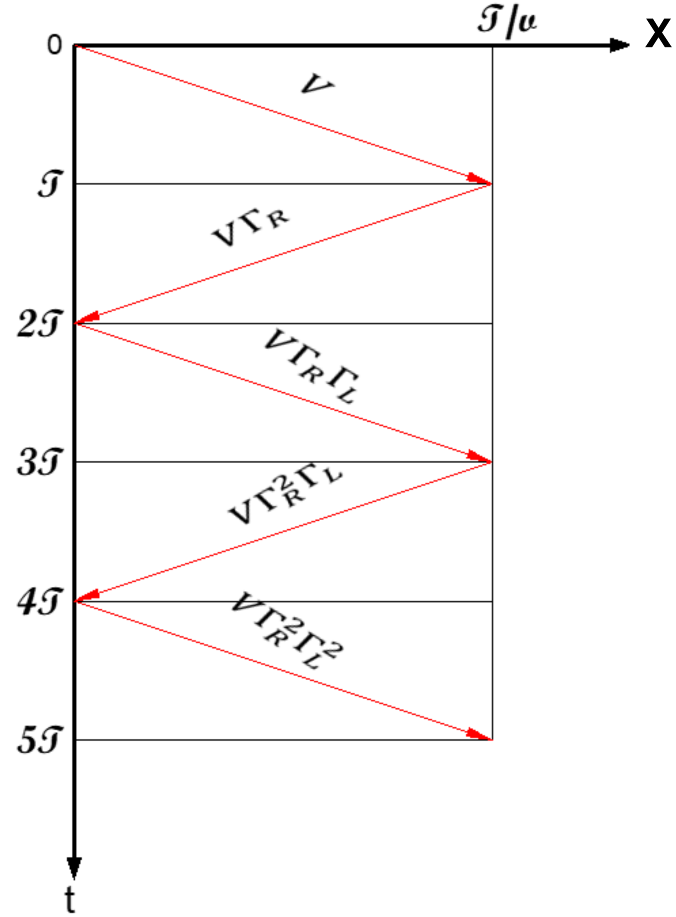
At time t=0 the switch closes and the ideal voltage source (Z_L=0) is applied to the transmission line of electrical length τ.
This launches a wave with a voltage amplitude of V and a current amplitude of V/Z_0 down the transmission line
At t = τ the waves reaches the load. If $R_l \neq Z_0$ there is a reflection
At t = 2 τ , the reflection from the load reaches the source. If $R_s \neq Z_0$ there is a reflection. The original voltage is also present
At t = 3 τ, the reflection from the source reaches the load, etc

Bounce diagrams are a useful tool to follow time response.

(A more mathematical formulation is given in “Pulse Response of Coaxial Cables”, LBNL Counting Note, Q. Kerns. F. Kirstem. C. Winningstead, July 1966 deals with losses in coaxial lines as a function of time)

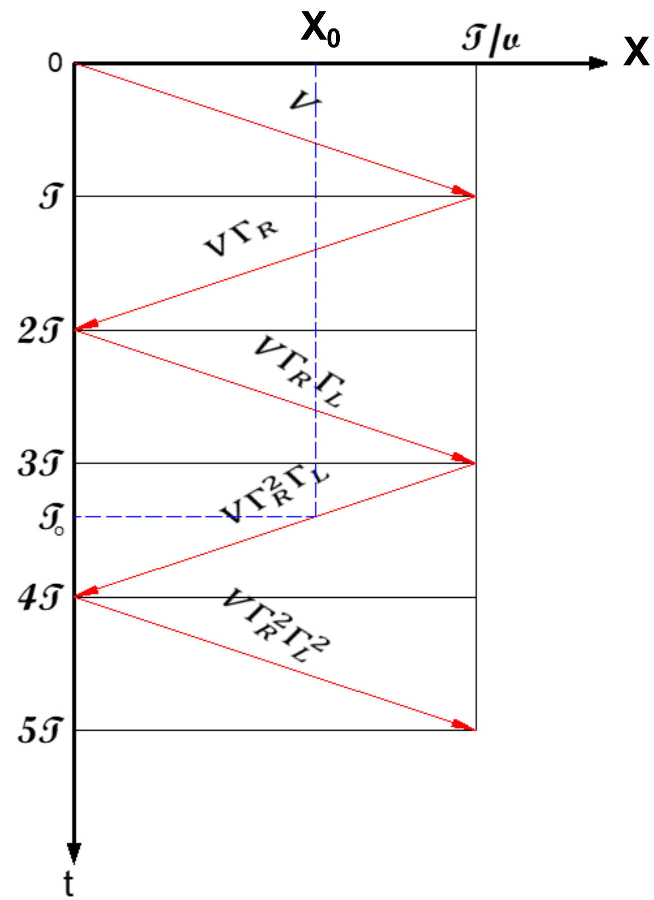
Bounce Diagram

- Horizontal axis: position
- Vertical axis: time
- Vectors: leading (or trailing) edge of TL waves, labeled with voltage (current) amplitude
  - Amplitude is product of incident wave and reflection coefficient at discontinuity
- Determine voltage (current)
  - As a function of position, at a specific time
  - As a function of time, at a specific position



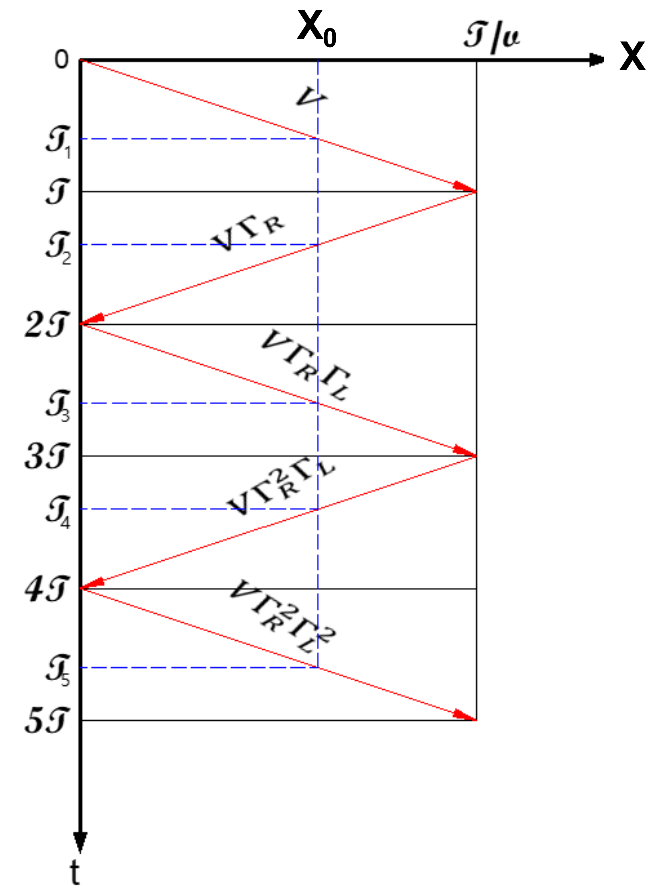
Bounce Diagram Interpretation: $t = \tau_o$

- Mark τ_o on the time axis
- Draw a horizontal line at τ_o
- Draw a vertical line from the intersection of the τ_o line and the wave vector, position X_0 is the location of the leading edge of the wave
- Voltage along TL to the left of x_0 is the sum of all wave vectors intersecting an imaginary line at x_0^- and to the right it is the sum of the vectors intersected at x_0^+
  - $V(x < x_0, \tau_0) = V + V\Gamma_R + V\Gamma_R\Gamma_L = V(1 - \frac{1}{2} + \frac{1}{2})$
  - $V(x > x_0, \tau_0) = V + V\Gamma_R + V\Gamma_R\Gamma_L + V\Gamma_R^2\Gamma_L = V(1 - \frac{1}{2} + \frac{1}{2} - \frac{1}{4})$



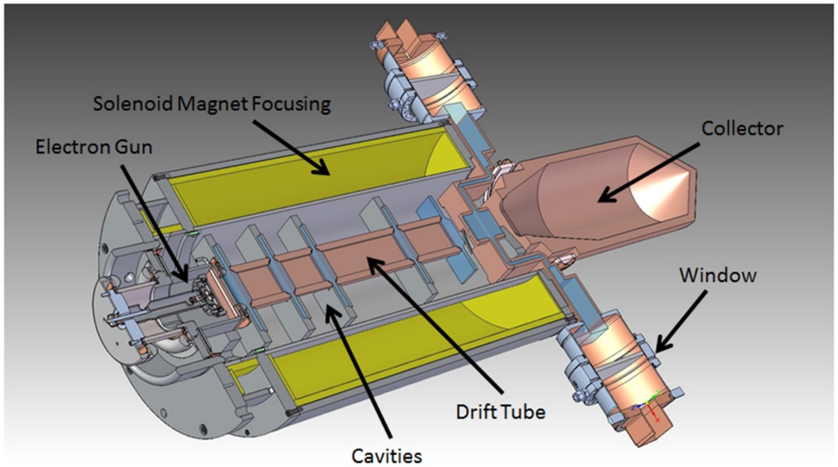
Bounce Diagram Interpretation $X = X_0$

- Mark X_0 on the position axis
- Draw a vertical line at X_0
- Draw a horizontal line at each intersection of the X_0 line and a wave vector. Each τ_N is the time when the new wave fronts arrive at X_0
- Voltage at X_0 versus time is then:
  - $0 \to \tau_1^-$ $\quad 0$
  - $\tau_1^+ \to \tau_2^-$ $\quad V$
  - $\tau_2^+ \to \tau_3^-$ $\quad V + V\Gamma_R$
  - $\tau_3^+ \to \tau_4^-$ $\quad V + V\Gamma_R + V\Gamma_R\Gamma_L$
  - $\tau_4^+ \to \tau_5^-$ $\quad V + V\Gamma_R + V\Gamma_R\Gamma_L + V\Gamma_R^2\Gamma_L$
  - $\tau_5^+ \to \tau_6^-$ $\quad V + V\Gamma_R + V\Gamma_R\Gamma_L + V\Gamma_R^2\Gamma_L + V\Gamma_R^2\Gamma_L^2$
- The TL voltage $\to V$ as the wave transients "damp out" over several transit times



Klystrons

- Purpose: Use pulsed electrical power to amplify high frequency radio frequency waves.
- 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
- Voltage across the electron gun, known as beam voltage, referring to the electron beam within the klsytron. This is the voltage the modulator must produce.
- An RF input is introduced in the upstream "buncher" cavities to group the beam into electron bunches. This pattern of bunches is transferred into an RF output via a downstream "capture cavity" and transmitted through the "window" that can pass RF but serves as a vacuum/gas seal.



A klystron "beam stick" has the electron gun, the collector and the solenoid but not the cavities; can be useful for modulator testing

Klystron Load Constraints

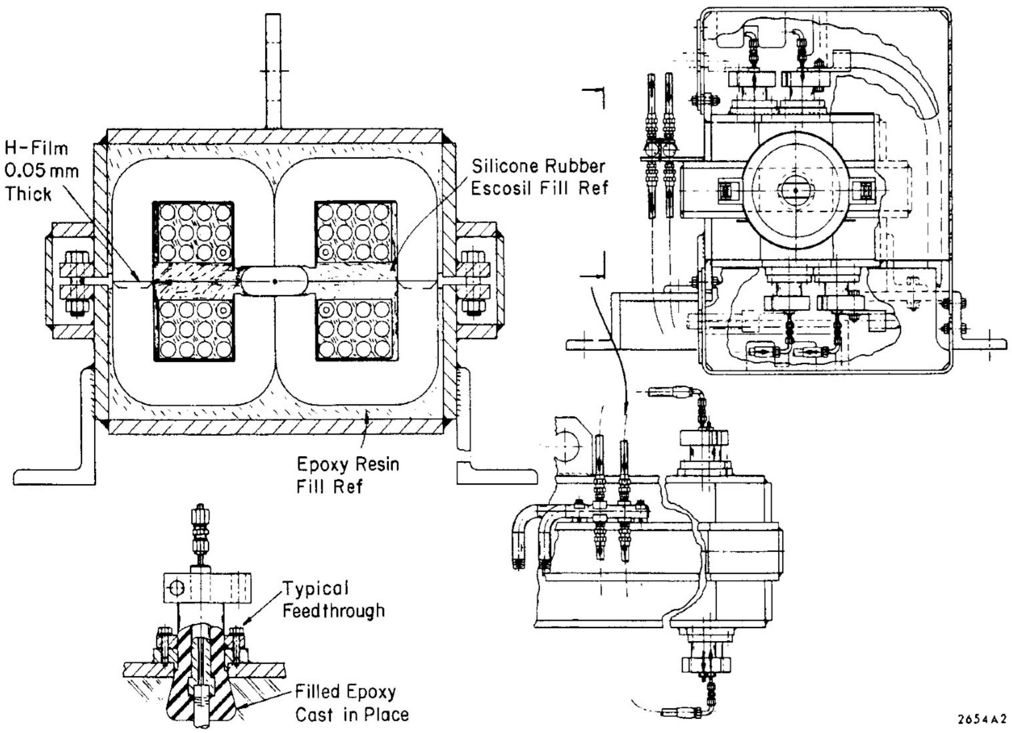
- Amplifiers: output regulation limited by input regulation
  - Low level RF (LLRF)
  - Beam acceleration voltage
    - RF phase α beam voltage
    - 0.1º phase stability typically required
    - Necessitates beam voltage stability to <50 V on >100 kV, <500 ppm
      - LCLS critical stations require ~30 ppm
  - Beam focusing fields (typically solenoid current)
- Electron beam device, operates with space-charge limited emission
  - $I_{beam} = \mu V^{1.5}$ forward
    - Reverse characteristic is a diode with a breakdown voltage much less than peak forward
  - Perveance, μ, typically ~10^{-6} ("microperveance" of 2 -> perveance of 2 10^{-6})
  - $Z = V/I = 1/(\mu V^{0.5})$
  - $P_{beam} = VI = \mu V^{2.5}$, $P_{RF} = P_{beam}$ * efficiency (typical, RF efficiency range 30 – 70%)

Beam Kickers

- Purpose: selectively deflect a portion of a charged particle beam into an alternative transport channel
- Three types:
  - Lumped inductance
    - Kicker is an electromagnet that can be modeled as a simple inductor.
    - Beam is only deflected by magnetic field
    - Requires a high current modulator
  - TEM mode transmission line structure
    - Parallel plates for a transmission line.
    - Equal kick from E and B.
    - Kicker presents a fixed impedance to the modulator
    - Terminated into a matched impedance to avoid reflections
    - Very fast, can be used in systems with small inter-bunch spacing
  - Lumped element (combination of both)
    - Use many magnetic blocks to contribute kick.
    - Utilize capacitors between the supply and return between each block.
    - The combination of inductors and capacitors forms a transmission line.
    - Mostly magnetic kick with some E-field contribution.
    - Limited rise time by the characteristic frequency of a single ferrite capacitor cell.

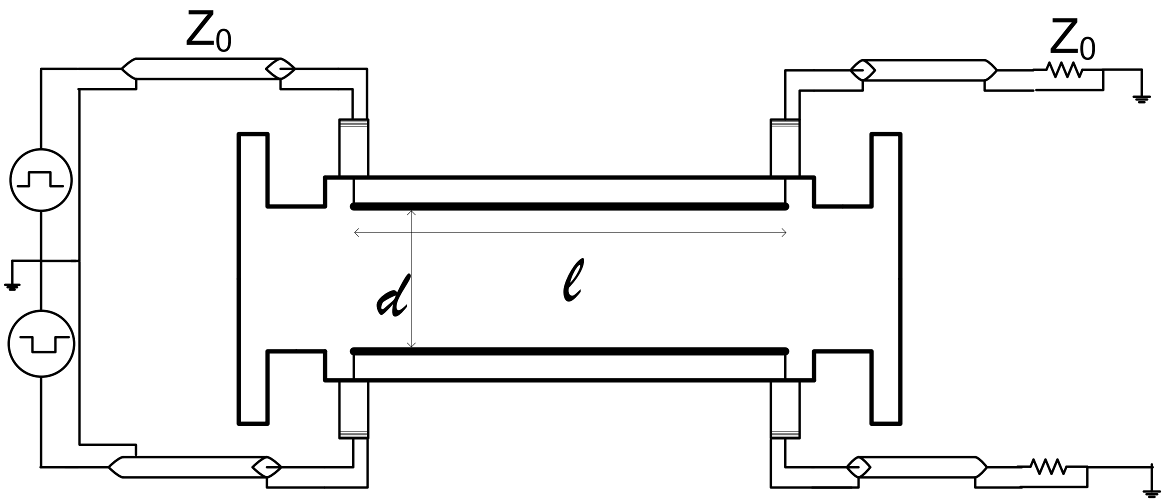
Magnetic Kicker

- To first order modeled as an inductor, with fully magnetic kick.
- Requires high current modulator
- Carefully selected core material based on pulse needs.
- Full sine or half sine, ring with capacitor
- Trapezoidal, driven with bus voltage.
- Be mindful of eddy currents, especially in the beampipe.



TEM Mode Transmission Line Structure

- Transmission lines, TEM mode kicker, and loads have matched impedance allowing for fast field rise and fall times. *Fill-time = length* speed of light*
- Loads can be located far from magnet via transmission lines. $Z = \sqrt{\frac{L}{C}}$
- For a parallel plate geometry and relativistic particles, $\theta = \frac{4 \cdot l \cdot V}{U_{eV} \cdot d}$ where V is the voltage magnitude on each plate, assumed to be equal and opposite polarity, and U_{ev} is the beam energy. Equal contribution from electric and magnetic fields.



Lumped Element Transmission Line Kicker

- Greater deflection field than magnetically loaded
- $Z = \sqrt{\frac{L}{C}}$
- $fill\ time = N * \sqrt{LC} = \frac{L_{total} \times I}{V} \propto B \times Vol_{gap}$
- Can be isolated from beam with coated beam pipe