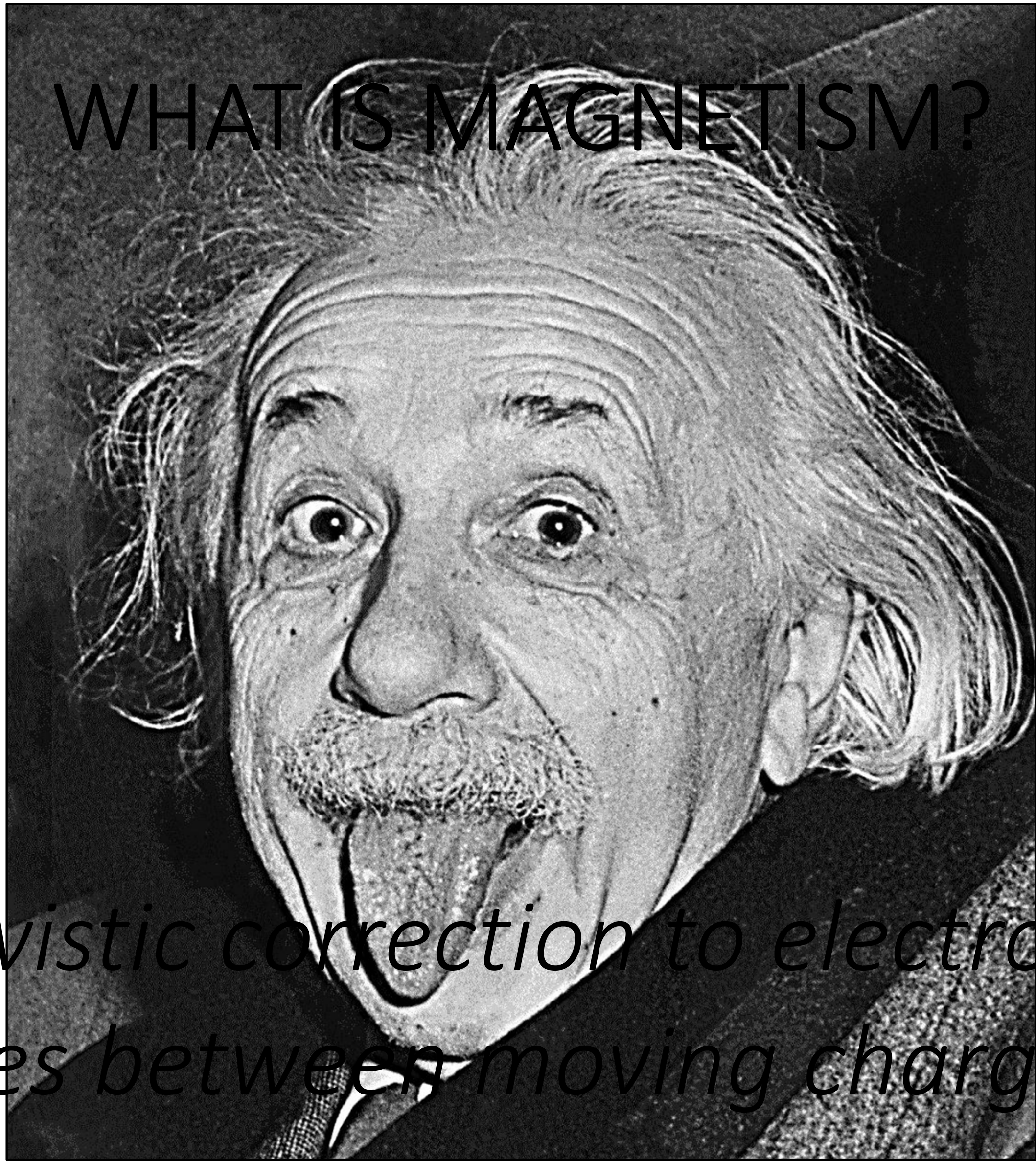
MAGNETICS
Inductor Basics

AGENDA

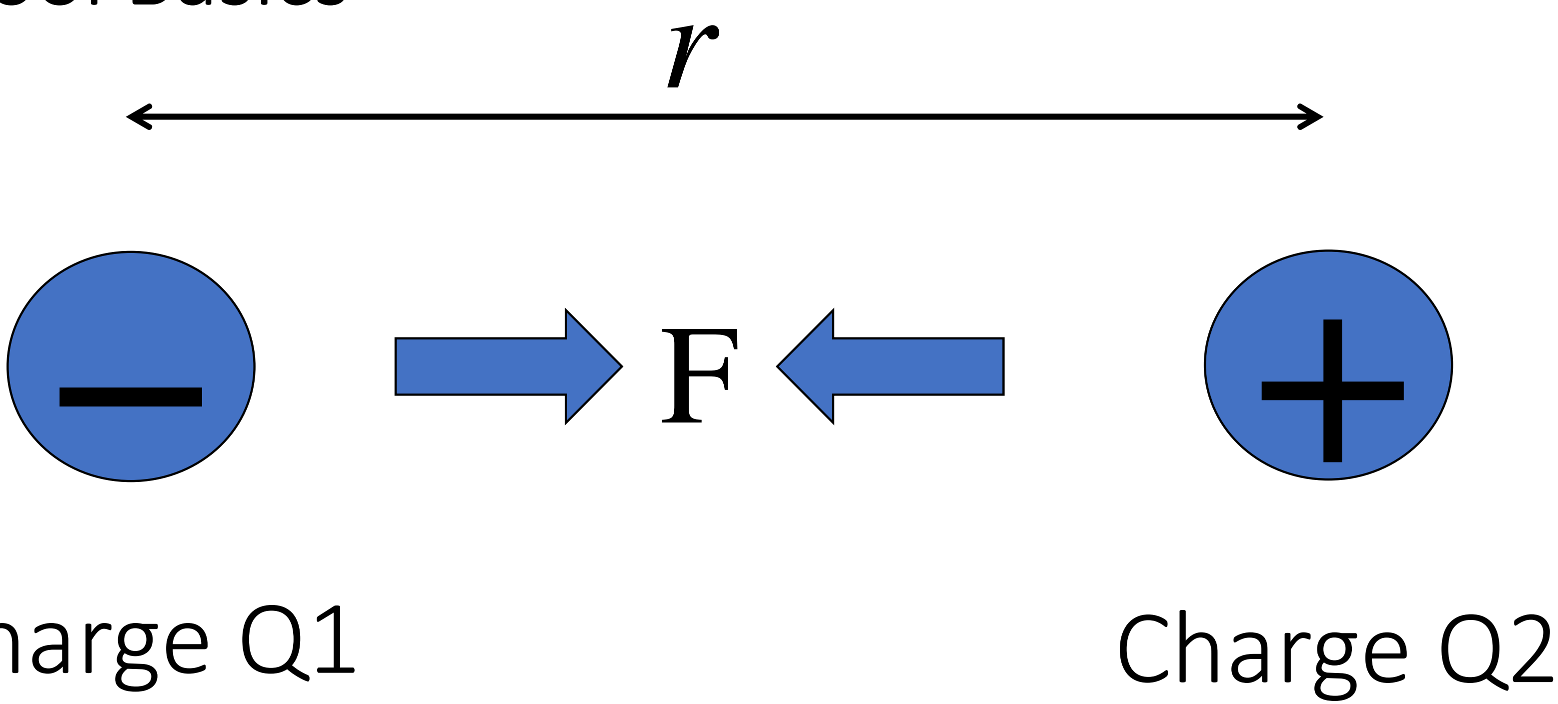
- Magnetism – What is it?
- Common Magnetic Components
- Inductor Basics
- Inductor Geometries
- Basic Equations of Operation
- Uses of Inductors
- Practical Applications & Limitations
- The Hysteresis Loop
- Gaps – Why and How?



WHAT IS MAGNETISM?

"Relativistic correction to electrostatic forces between moving charges"

School Basics



$$F = \frac{Q1\ x\ Q2}{r^2}$$

Coulomb’s law

School Basics

r

F

Charge Q1

Charge Q2

$$F = \frac{Q1\ x\ Q2}{r^2}$$

Coulomb's law

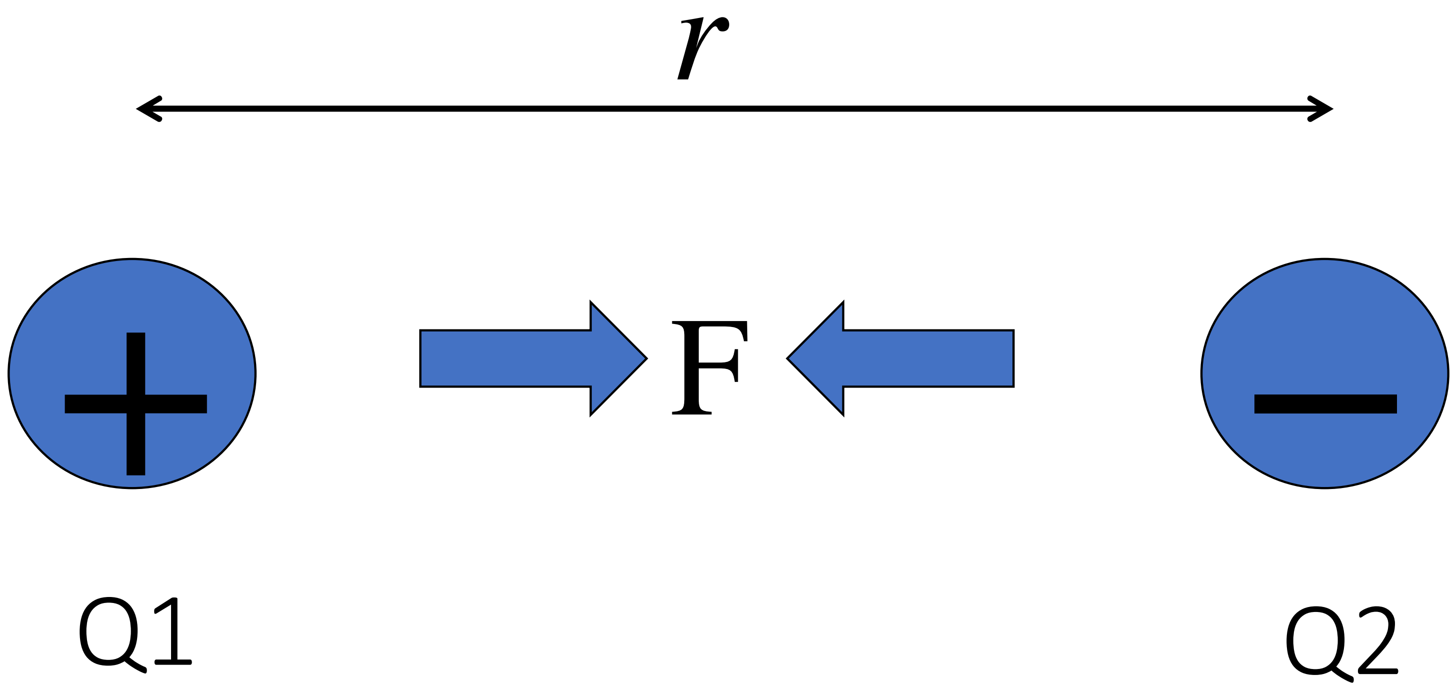
Magnetics Basics

- Charge on the electron (basic unit of charge) is:

$$-1.602176565 \times 10^{-19} \text{ Coulombs}$$

- This is a derived number, 1C being defined as the amount of charge moved in 1s at a current of 1A
- Never been known to vary under any condition, static or moving, and exactly equals the charge on a proton, so total charge in a system never varies if no other charge is introduced or removed (charge conservation rule).
- So for single stationary charges Q1,Q2, and r are constant so Force is constant
- What happens if Q2 moves? (Current is moving charges.)

Magnetics Basics



$$F = \frac{Q1 \; x \; Q2}{r^2}$$

Magnetics Basics

- r is changing as Q2 moves, thus F changes.
- For each new value of r, say r_{new}:

$$F = \frac{Q_1 \, x \, Q_2}{{r_{new}}^2}$$

- But…Hendrik Lorentz (Dutch physicist in the 19^{th} century) suggested that as an object moves faster in relation to another stationary one, time slows down at the moving object from the point of view of the stationary object.
- The moving object still seems to get from A to B (e.g. a charged particle goes from one end of a wire to another) so if time has slowed, then distance must have shrunk for the object to still get there.

- So, if the stationary and moving objects are charges, each sees a force:

$$F = \frac{Q_1 \, x \, Q_2}{{r_{reduced}}^2}$$

- The difference between this force due to the charges moving and the force when the charges are stationary (Coulomb's Law) is a new force which always increases force F in Coulomb's Law.

- **THE EXTRA FORCE IS CALLED MAGNETISM**

- But, it is just the extra electrostatic attraction/repulsion between charges due to their relative motion.

Magnetics Basics

In permanent magnets, the effect is because of motion (spin) of electrons. In non-magnetic materials the attractions and repulsion are distributed so as to cancel out. In a permanent magnet, the atoms are able to align in ‘domains’ so that the attractions and repulsions align and sum together.

Electromagnetism is caused by motions of electrons as electrical current.
Individually electrons move locally at about 1,000,000 mm /second (Fermi velocity).
A signal though wire propagates at about the speed of light 3 x 10^{11} mm/s
An individual electron gets longer distances at about 1mm/second.

Its this ‘drift’ velocity that causes magnetic force. Nowhere near the speed of light but there are so many electrons that even at this speed the magnetic force is felt.

Common Magnetic Components

- Single Inductors (e.g., 4800 Series)
- Dual Winding Inductors (two inductors coupled together on one core; e.g., 4300 Series)
- Current Transformers (ditto)
- Pulse Transformers (ditto)

So all products are inductors or “coupled” inductors

We restrict this training material to inductors.

Inductor Basics

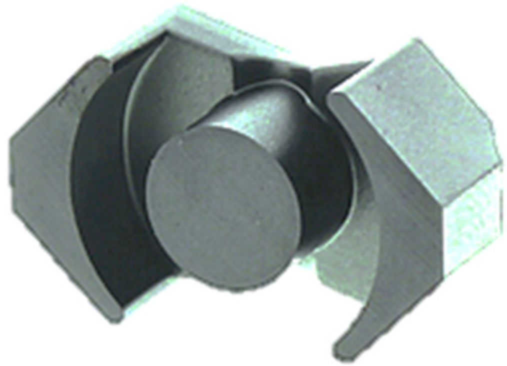
An inductor is a conductor (wire) that produces a magnetic field around it – a volume where other conductors or magnets feel a force.
All wires do! Even a straight wire ~ 30nH /inch

In an inductor *component*, the wire is normally coiled as the magnetism in each turn reinforces the magnetism in the adjacent turns and vice versa. (Inductance proportional to turns squared)

A suitable core 'conducts' magnetic field through it much better than air. It has higher 'permeability' or low 'magnetic resistance' compared to air. It also has it's own mini magnets (domains of aligned atoms) that can align with the imposed field and add to it.

So cores are not just a conduit for magnetic field – they intensify it

CORE GEOMETRIES

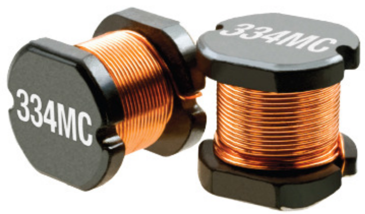


Inductor basics

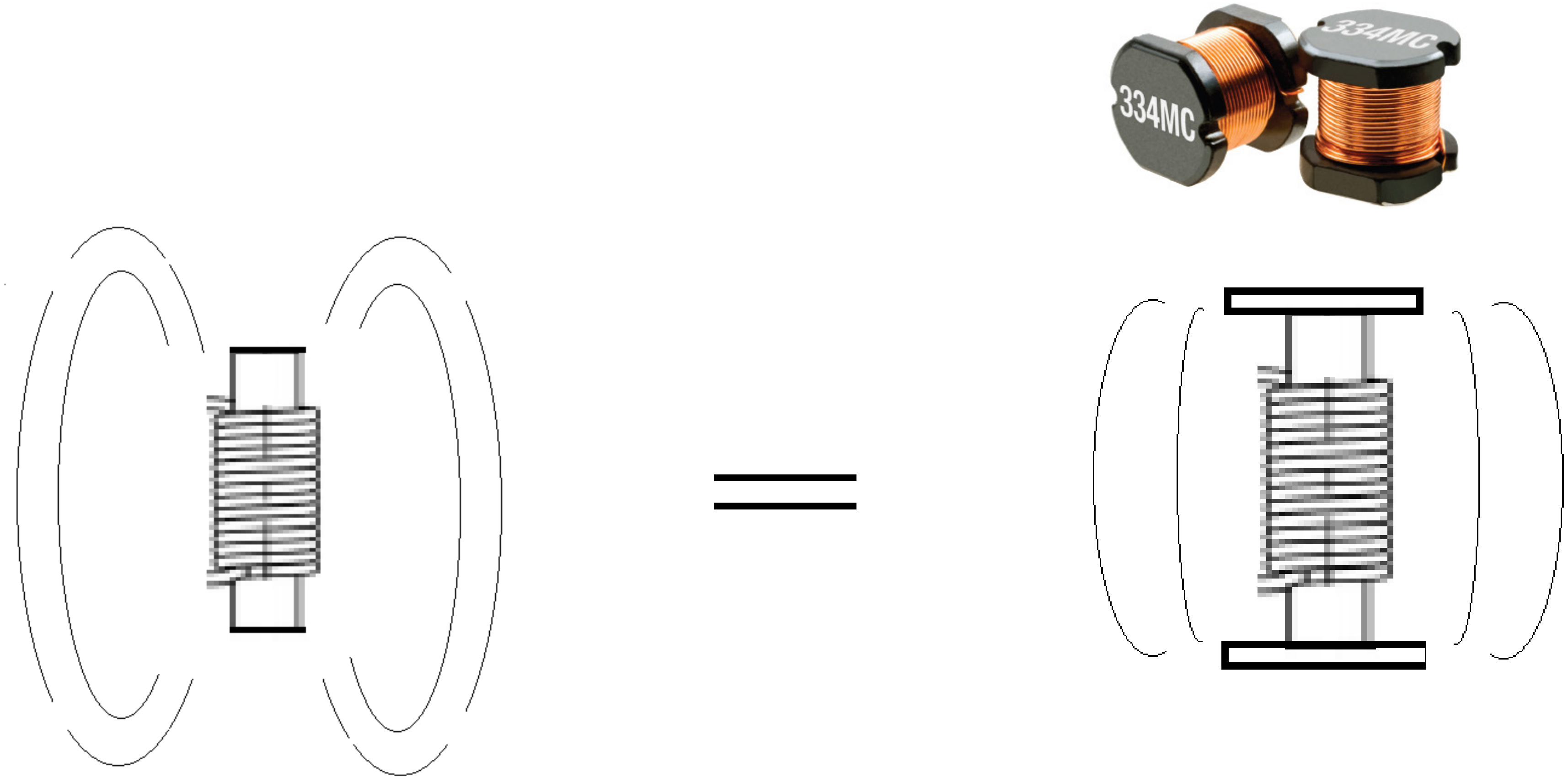
An inductor can be formed on many different core shapes

They're all basically the same just in different convenient forms

Rod Core Drum Core Drum Core E Core Toroid
Shielded

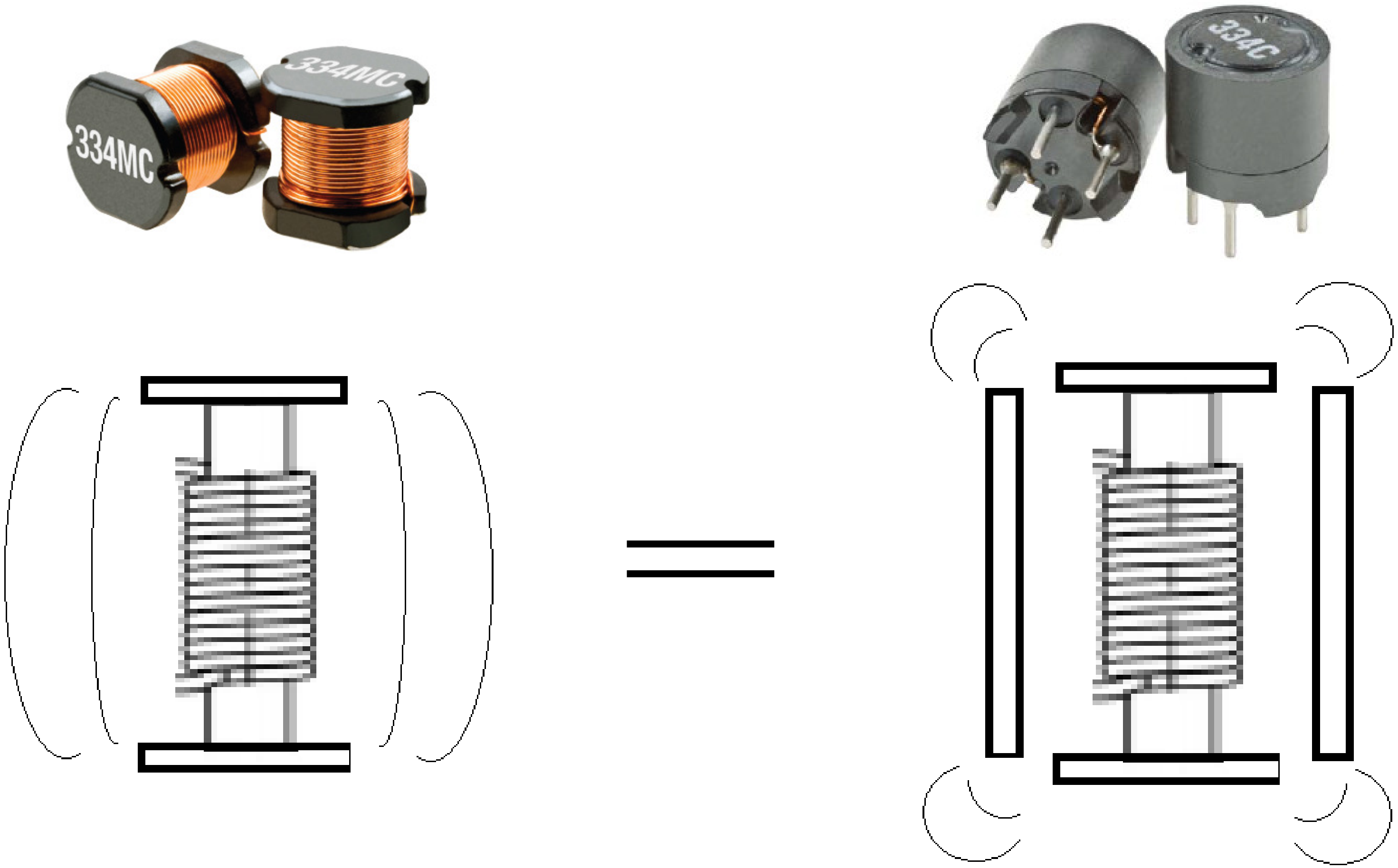


Magnetics basics

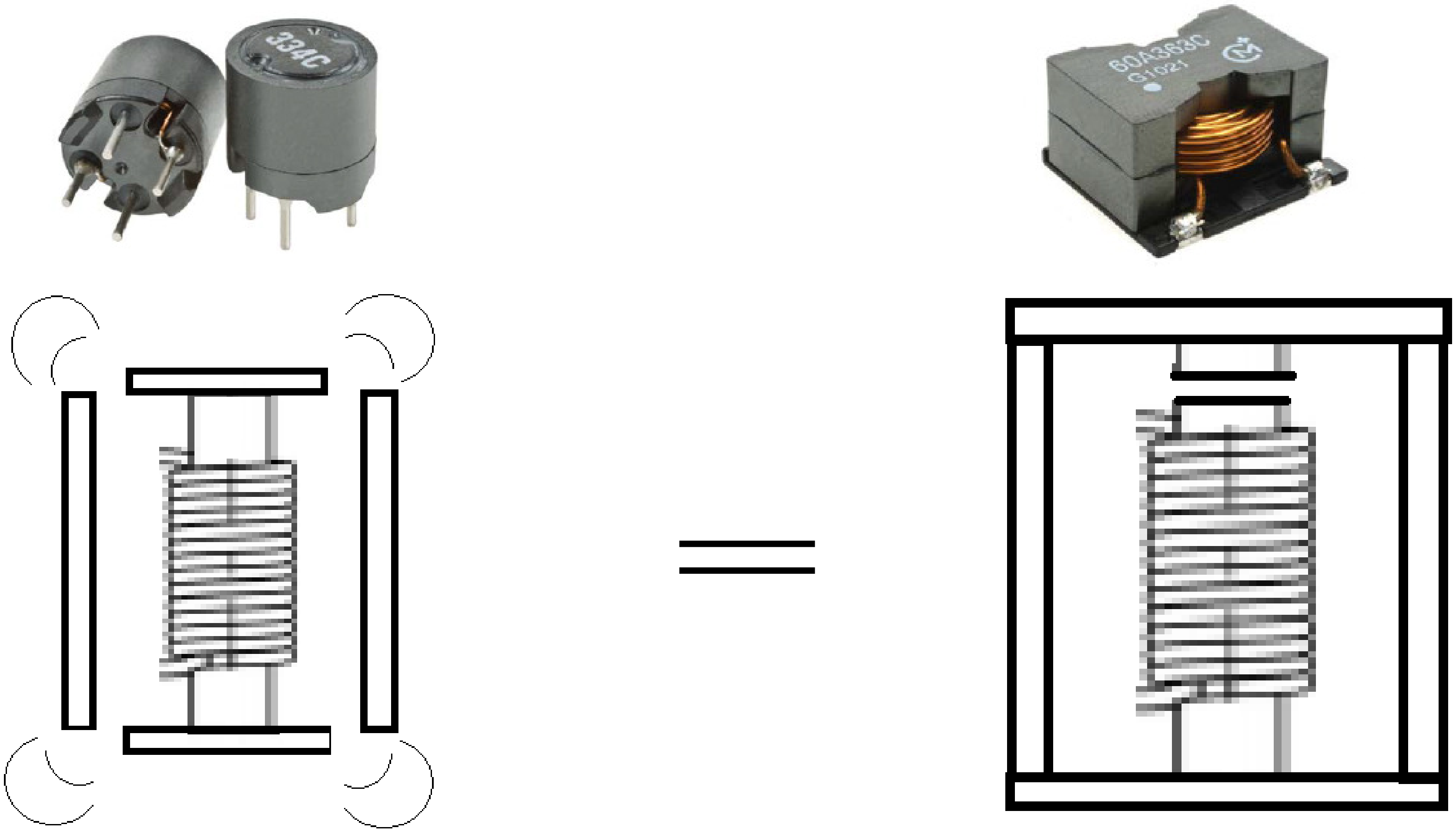


A drum core is a rod core with flanges to helpfully keep the winding in place and shorten the distance for the flux lines to go

Magnetics basics

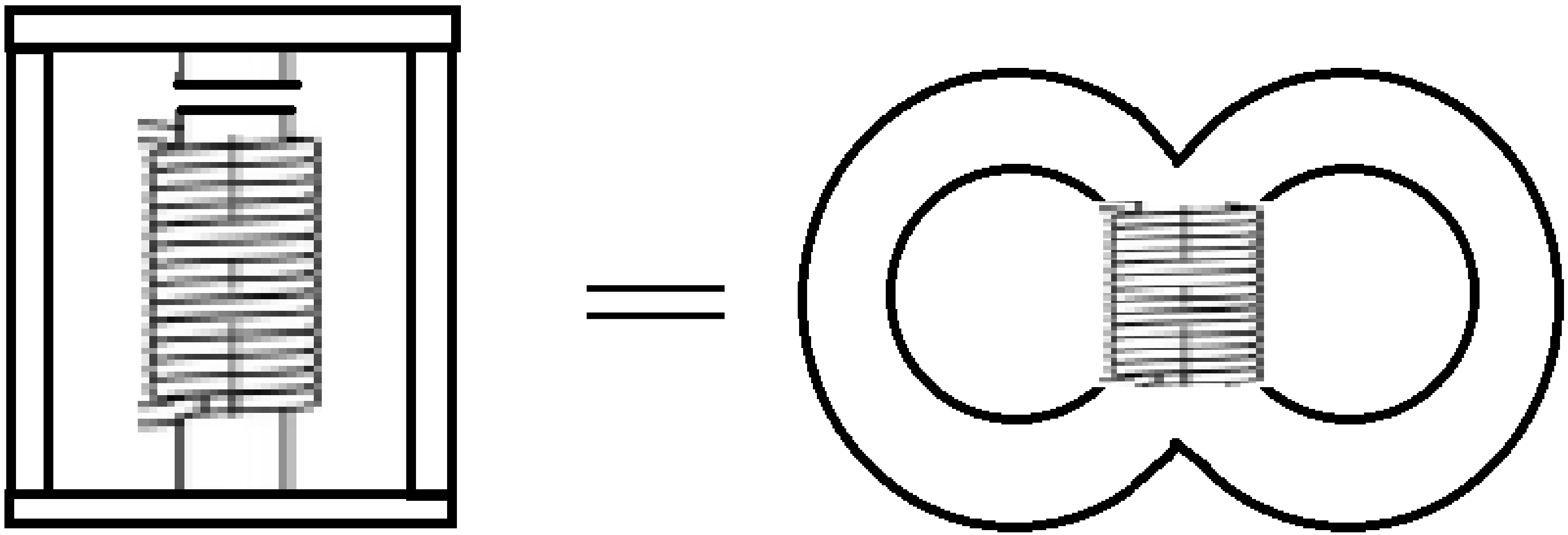


A screened drum core is a drum core with ferrite around to route the flux lines and produce less external flux



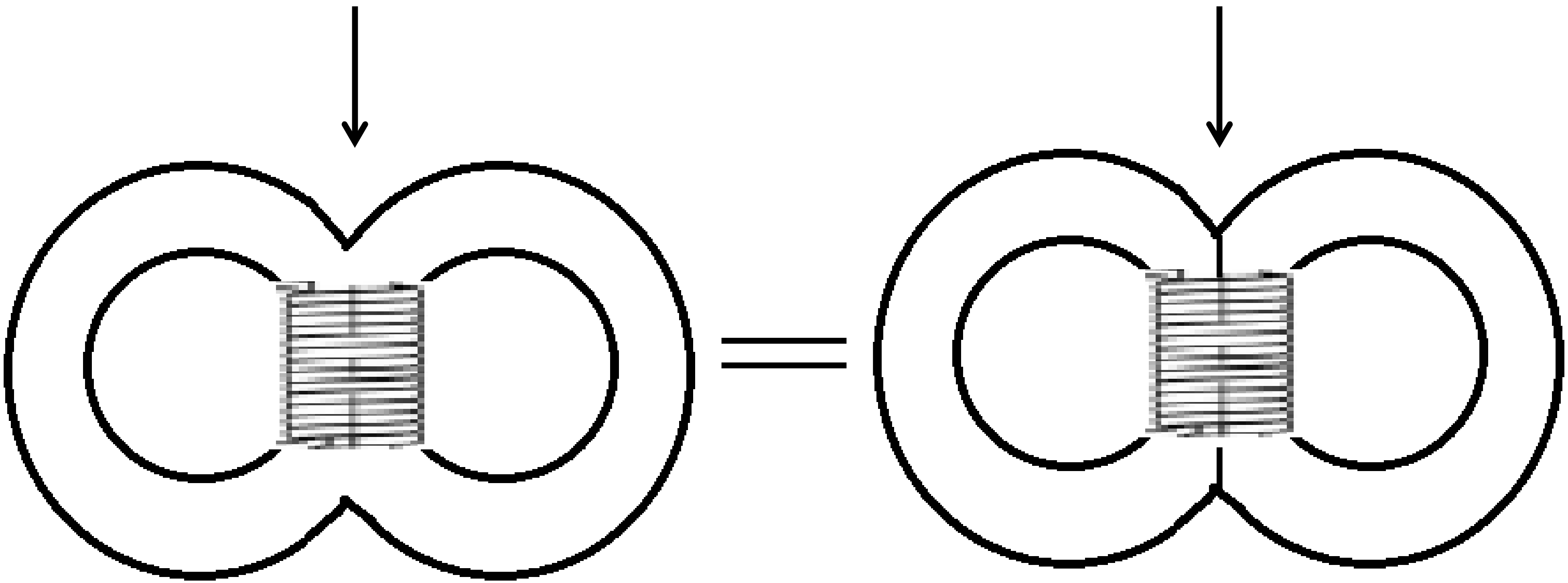
An E core is a screened drum core with no gaps or if one is wanted, it is placed in the centre limb or middle of the side limbs. The open side can be any size from zero = pot-core to large

Magnetics basics



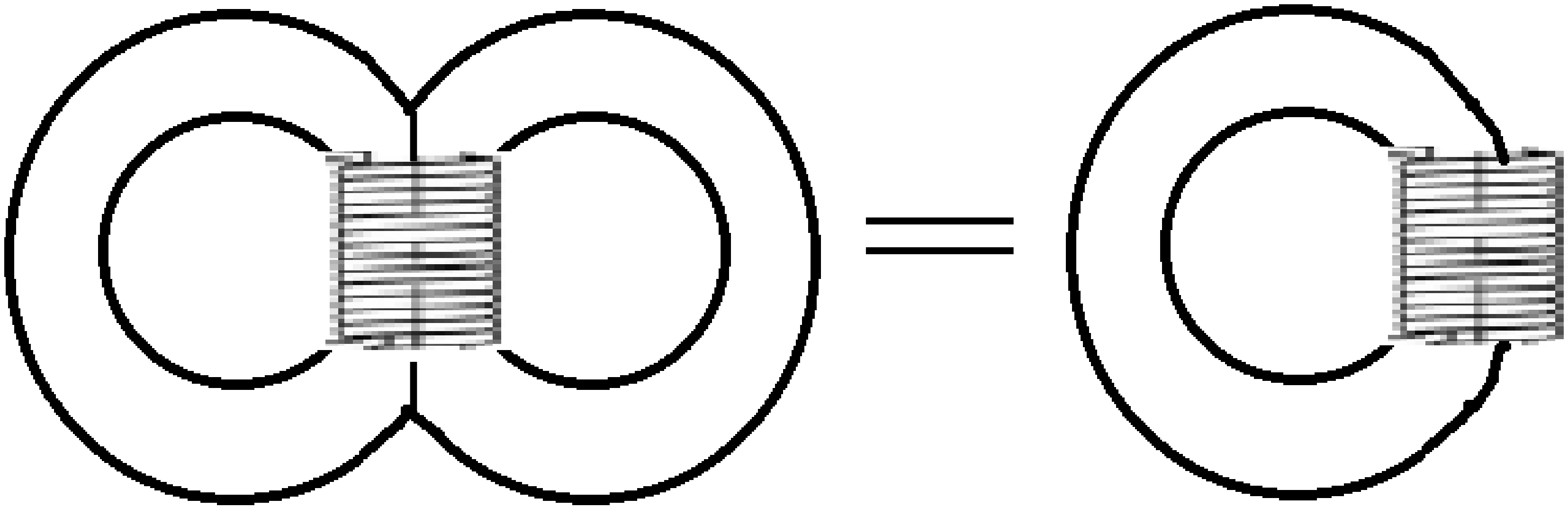
An E core could have it's corners rounded
(Can you see where we're going?)
Gap could be in the center limb under the winding

Magnetics basics

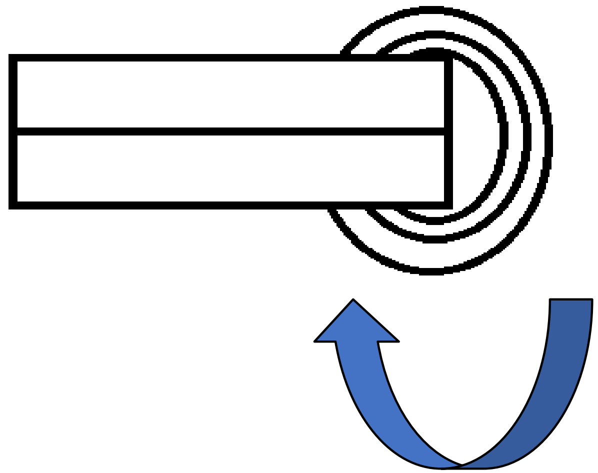


An E core with rounded corners is the same as two ring cores side by side

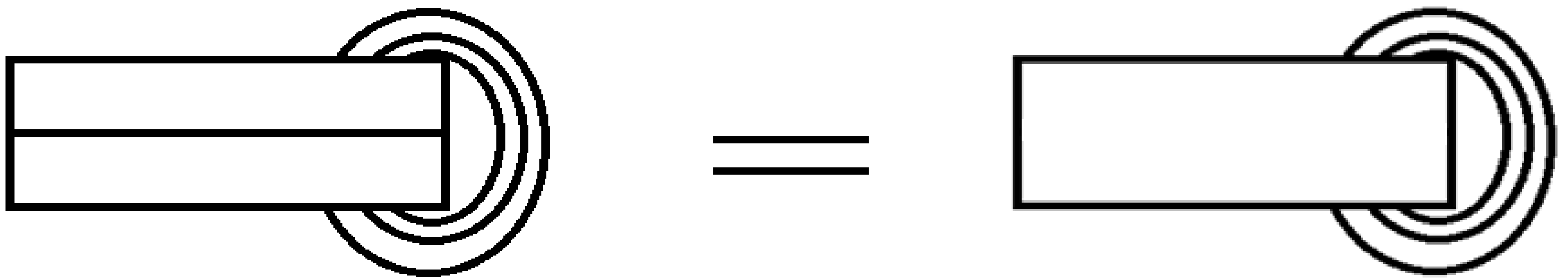
Magnetics basics



Two ring cores can be folded round to be one ring core = a simple toroid core



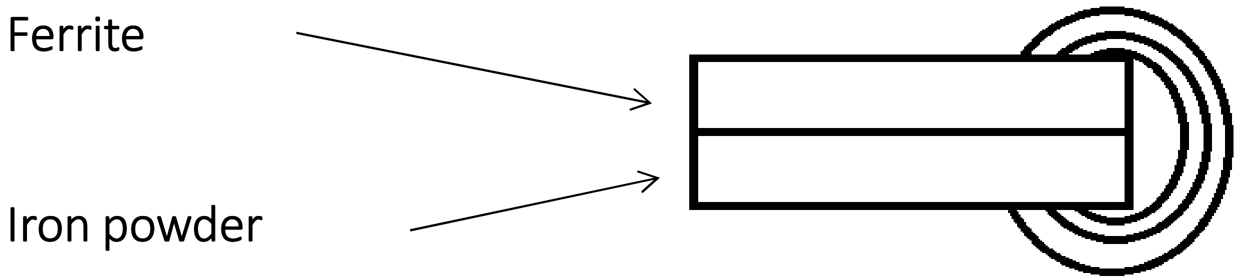
Magnetics basics



Point is all inductors are topologically equivalent, so can use the same basic equations for all core shapes, sizes and materials

NB you can stack cores together like this eg two identical doubles AL value doubles (= inductance per turns squared) and cross sectional area doubles
You can stack different materials! For combination of characteristics
You can stack a permanent magnet with a ferrite!

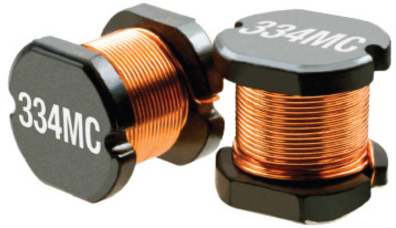
Example of stacking



Ferrite gives high inductance at light currents but saturates at high currents
Iron powder provides remaining (lowish) inductance at high currents.

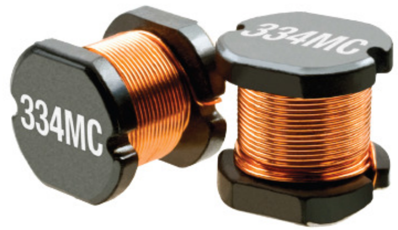
Useful for forward converters which can lose control at light loads

Inductor basics – practical considerations



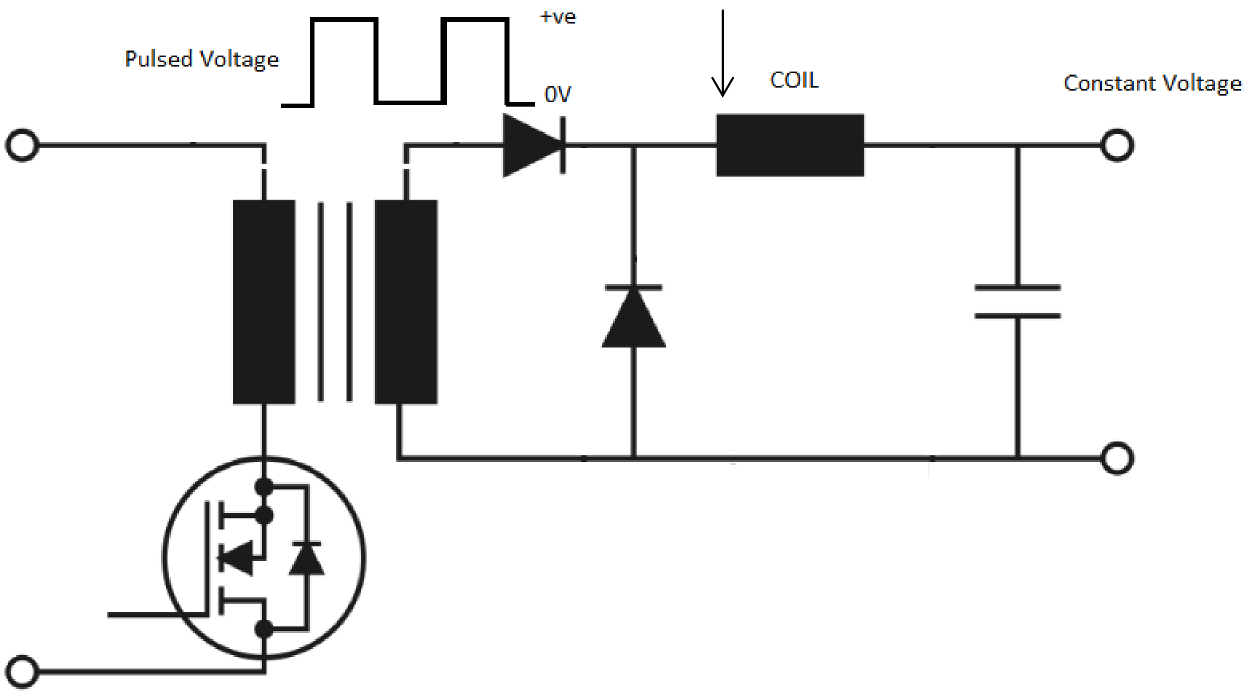
Drum core
Large external field – could cause interference
If field couples into another inductor you have a transformer!
Cores have polarity! Connect start (inner) to noise source for screening effect. Sometimes a dot, or marking orientation tells you
Start and finish always very close – risks flashover due to pinch point
 - so not very suitable for eg high voltage buck converters
Can also get breakdown to the core but depends on material
Cheap material but gap fixed
No plastic bobbin so cost saved
High self capacitance due to bundle of wires = low self resonance
SMT and through hole versions
Large effective gap means lots of turns for significant inductance (low AL value) = thin wire = high resistance = high loss

Inductor basics – practical considerations



Screening – make diode end of inductor the innermost

Start



Inductor basics – practical considerations

Shielded Drum core

Less external field less prone to pick-up
Again cores have polarity
Start and finish always very close –
Cheap material gap varies with shield
No plastic bobbin
But extra cost of shield and assembly
High self capacitance due to bundle of wires = low self resonance
SMT and through hole versions
More ferrite to contribute field = fewer turns for given inductance
(higher AL)
= less resistive loss but smaller gap means easier to saturate with DC

Inductor basics – practical considerations

E Core

Nearly no external field for ungapped core
Ext field for gapped core can be controlled by placement
Normally needs plastic bobbin especially for large cores but
Can use round/flat wire, metal stamping, foil, PCB tracks as windings
SMT versions need plastic bobbin or base plate
Two ferrite pieces so labour for assembly
Mating faces have to be ground flat and /or gapped so expensive
Start and finish of wind always close so breakdown issues
Great for PCB planar inductors
Can have E-E, E-I, EFD, ER formats etc
PQ format (as shown in pic) close to optimum use of ferrite but quite expensive. Ideally centre pole area should be 2 x each limb area

Inductor basics – practical considerations

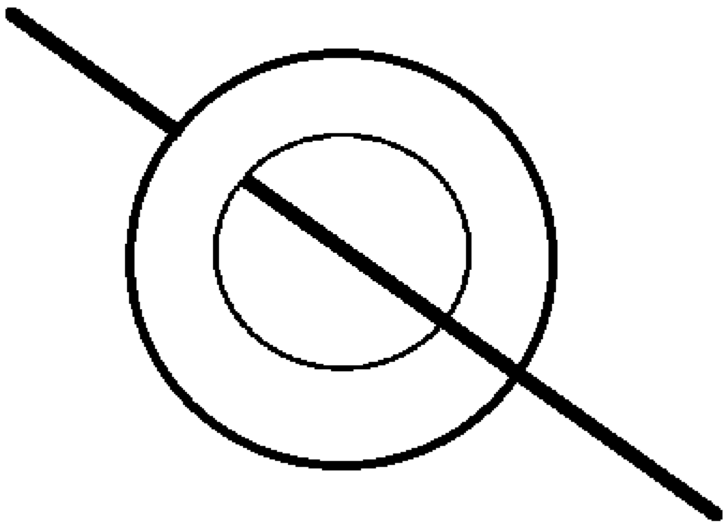
Toroids

No external field for ungapped core
A required gap has to be laser cut or distributed – fixed
Start and finish can be widely separated for low flashover
Worry about flashover to the core though – some coated
Winding can have low capacitance for high self resonance
High labour cost for hand wind or expensive machine for auto wind
Can't use winding space very well – space needed for shuttle
Mounting difficult – need base/moulding
No grinding so can be very low cost core
No polarity issues
Practically can only use round wire

Inductor basics – practical considerations

Toroids

This is 1 'turn'!!

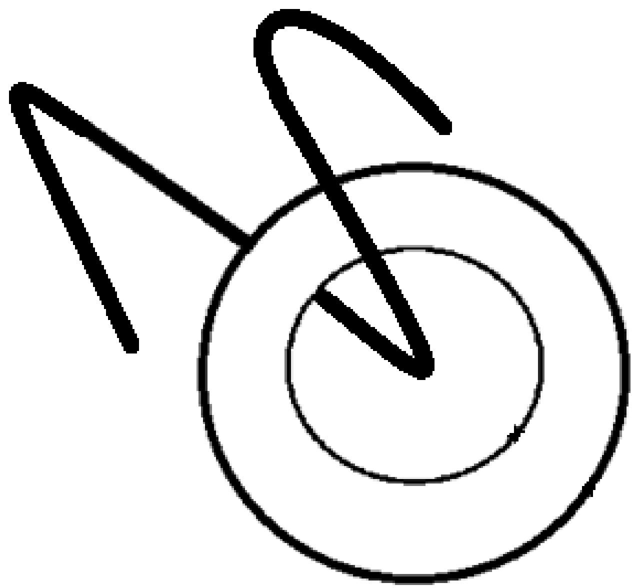


What counts is number of times the wire passes through the middle

Inductor basics – practical considerations

Toroids

Still 1 'turn'!!



What counts is number of times the wire passes through the middle

What is Inductance?

Constant moving currents produce constant magnetic fields (from before)

Changing currents produce changing magnetic fields which takes work

Voltage drives current, producing magnetism so the 'resistance' that the work is acting against is like an opposing induced voltage, which is what you actually see.

Faraday's law:
Induced voltage E = -constant x rate of change of current

The constant depends on the things which affect the strength of the magnetism ie number of turns and the material used for the core if any

The constant for a particular physical inductor is called ‘Inductance’

Rate of change of current = di/dt

so $E = - L \, di/dt$

‘ – ‘ because the voltage induced works to oppose the applied (driving) voltage

Magnetics basics

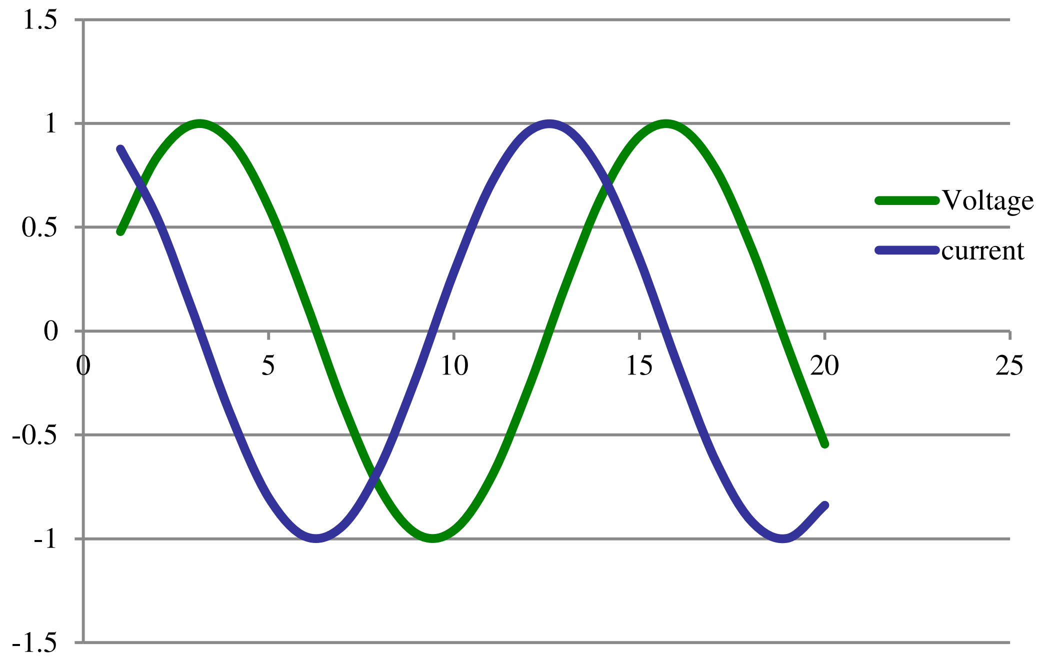
From the relationship E = -L di/dt:

Opposing voltage generated is highest when di/dt is highest so actual voltage (applied voltage – opposing voltage) is minimum when di/dt is highest)

Practically this means that for, say a sine wave, imposed directly across the inductor, current is minimum when voltage is maximum.

i.e. voltage peaks are 90 degrees ahead of current peaks

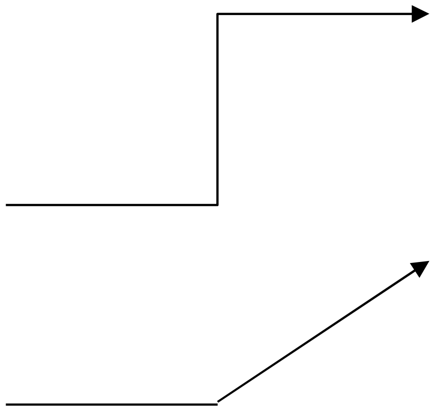
(In front or 'leading' just by convention)



Magnetics Basics

Also from E = - L di / dt

If E is a constant (i.e. a constant applied voltage like a pulse), L is fixed so di/dt is constant (i.e. a constant rate of change of current, or a steady, linear increase in current.



Voltage

Current

So any constant voltage or average voltage different to zero will cause ultimately infinite current (not good).

So average voltage across an inductor must be zero (compare with capacitor where average current must be zero).

What does a coil (inductor) do for you?

1. A resistance to AC

Ohm's Law applies to inductor circuits, so R = E/i

From before, E = -L $\frac{di}{dt}$ so resistance of our coil is

$$\mathbf{R = -L\frac{di}{dt} \times \left[\frac{1}{i}\right]}$$

So, equivalent "resistance" = -L / t , where t is pulse length, and time t = 1/f (frequency); thus,

equivalent "resistance" = f x L

What does a coil (inductor) do for you?

1. A resistance to AC cont …

A resistance that varies with frequency is called impedance Z so
Z = F x L or:

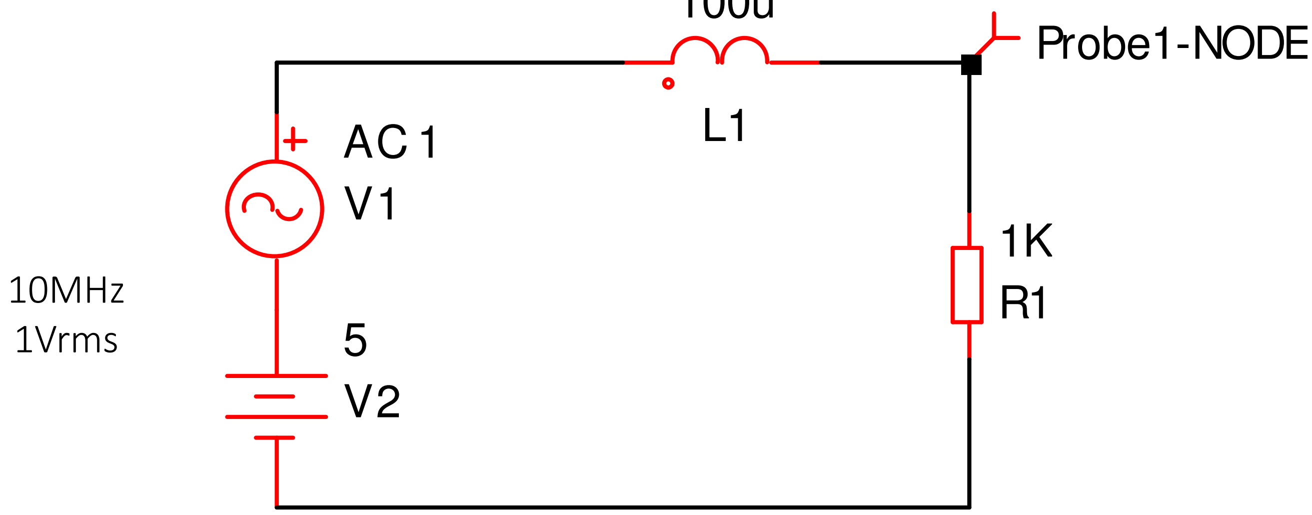
Z = 2 x Pi x F x L (2 x Pi) just so we can talk Ohms, Hertz, Henries

= ω L where ω = shorthand for (2 x Pi x F)
(we'll talk about 'j ω L' next)

So a coil produces an 'impedance' which increases linearly with frequency dependent on its inductance.

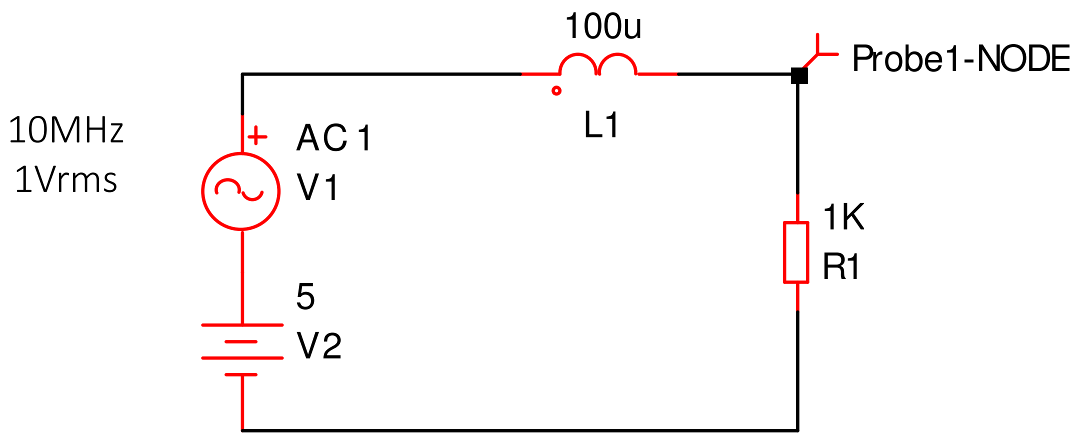
At DC, f = 0, so Z = 0 at f = infinity Z = infinity

L1 = 100 uH = Impedance of
6280 Ohms at 10MHz
(2 x Pi x F x L)



Probe voltage = NOT just a pot-down R1/(R1+6280))

...Because AC voltage dropped across L1 is not in phase with voltage dropped across R1 (current through R1 is leading the applied voltage from before) so can't arithmetically add.
Lead is not 90 degrees because the applied voltage is across a combination of R and L, not just across L



Have to include 'j' operator
Just a way of factoring-in the
Effect of the phase difference

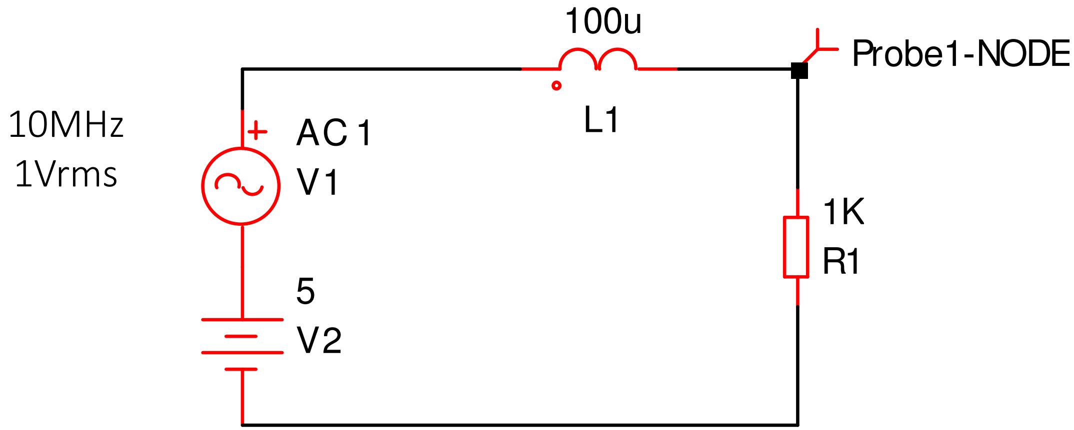
$$\text{Probe V} = \text{V1 x } \frac{R1}{(R1+j\omega L}$$

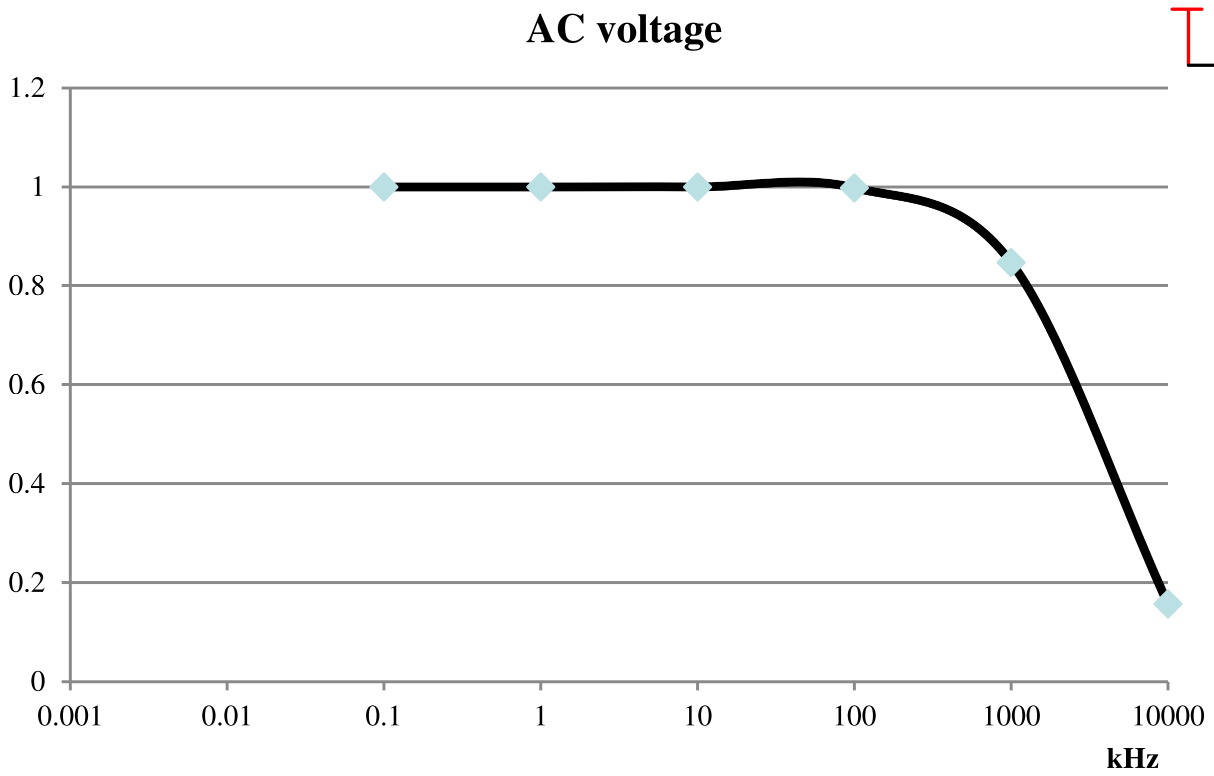
Doing the maths, actual relationship quite complex:

$$Probe\,V\ = V1\ (\frac{1}{(R1^2+\omega^2 L^2)}\sqrt{(R^4 + \omega^2 L^2 R^2}\ )$$

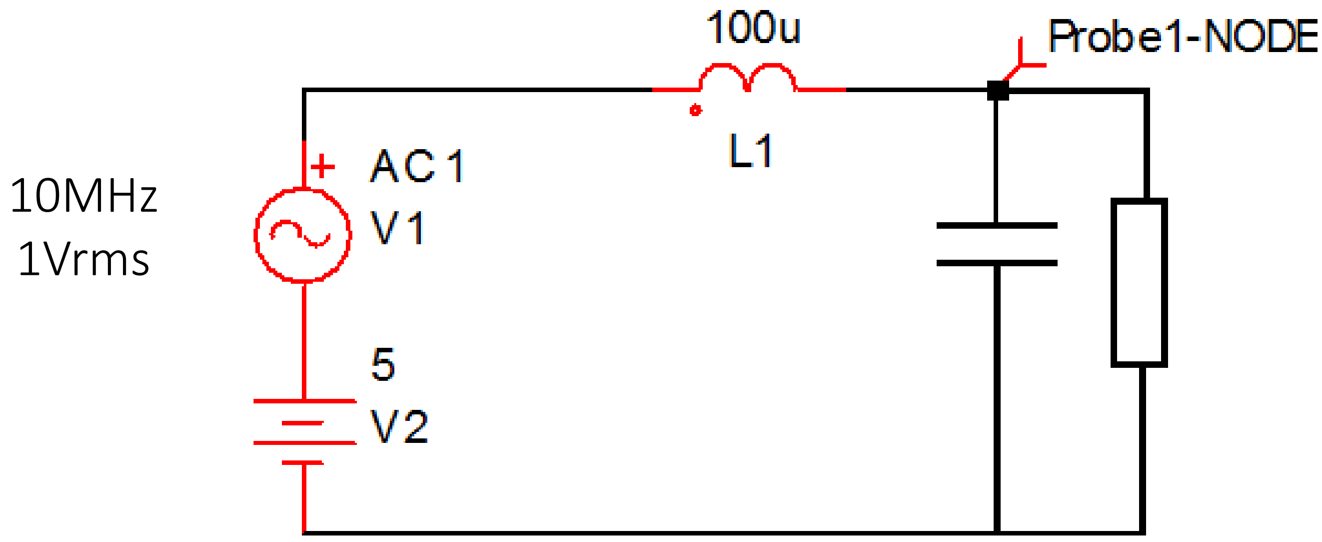
Actual phase lead is = $\text{Tan}^{-1}(\omega\ \ L\,/\,R)$

Plot the last equation:
Actual voltage has the 5V DC offset on top





Magnetics basics



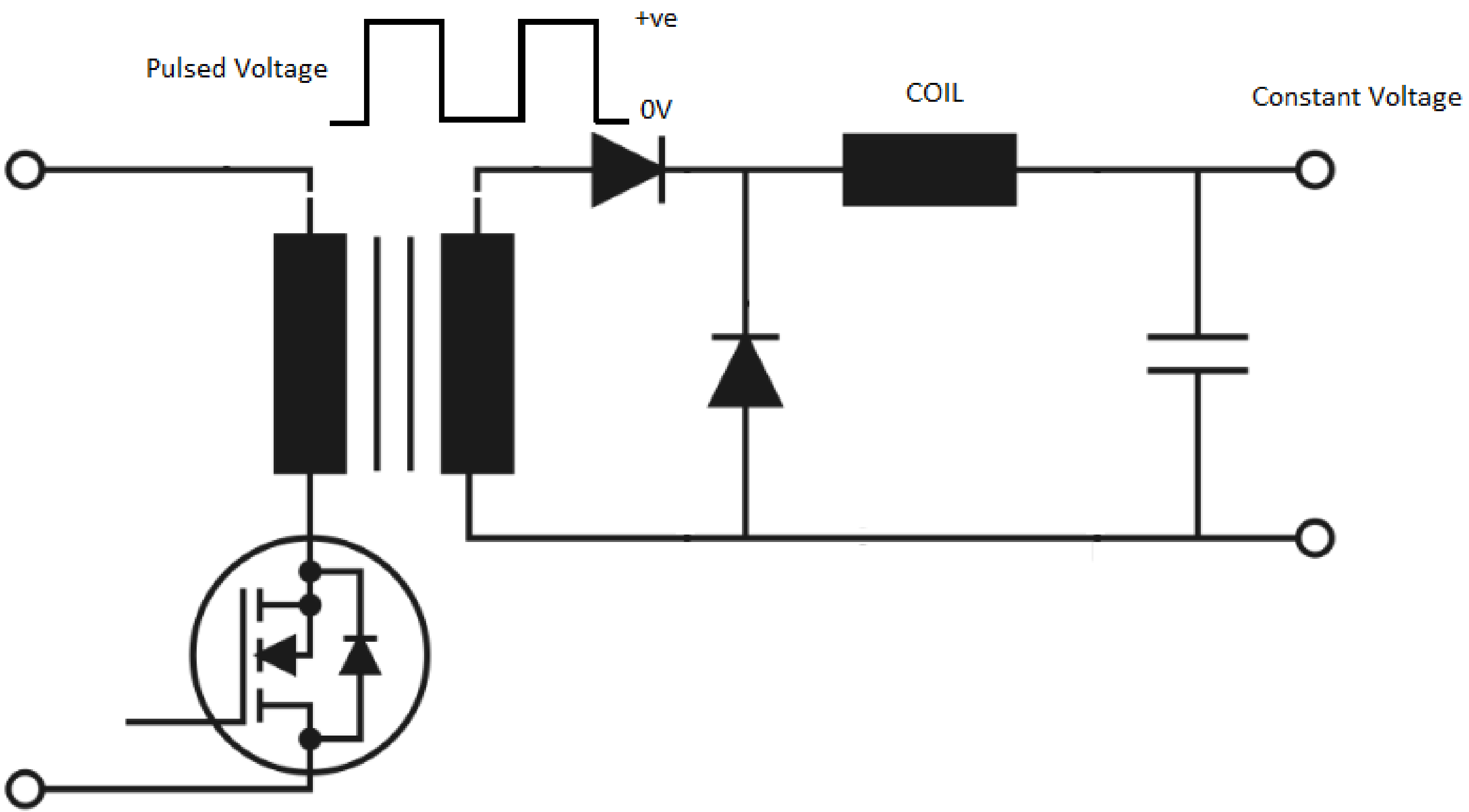
Add a capacitor and the attenuation is improved further and you now have a typical noise filter on the output of a DC-DC converter where the resistor is the load

Does it resonate and ‘ring’? Yes but resistor damps the effect and resonance is normally much lower than switching frequency

2. Energy storage – 2nd main use of inductors

When current flows in a coil, charges move and as a result a field of force is set up affecting other charges around.
Work is done (or energy expended) to set up the field.
This energy is 'stored' in the field so that when the charges stop movement (current stops) the field collapses and the energy is released.
Energy $E = \frac{1}{2} Li^2$
Characteristic can be used in electronics to even out current flow in for example a forward converter (like NPH15)

Voltage only available from the converter transformer in pulses
(transformers cannot pass DC)



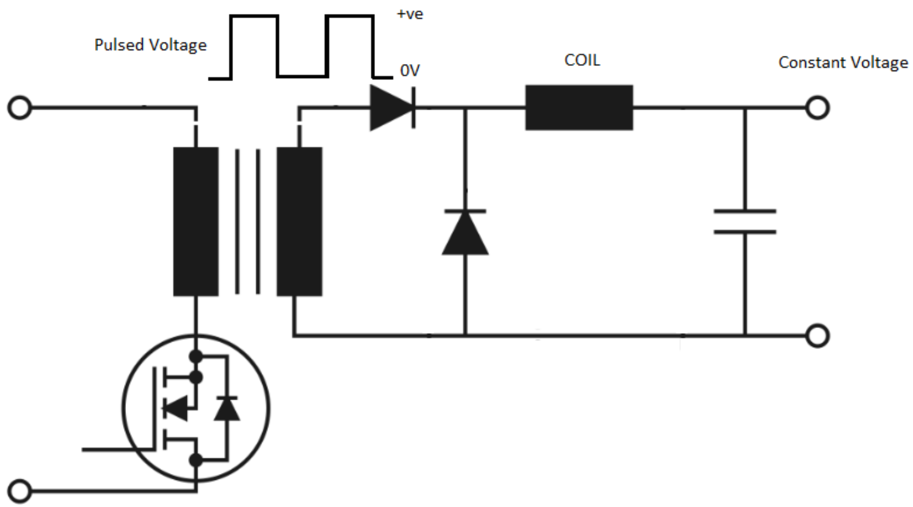
Magnetics basics

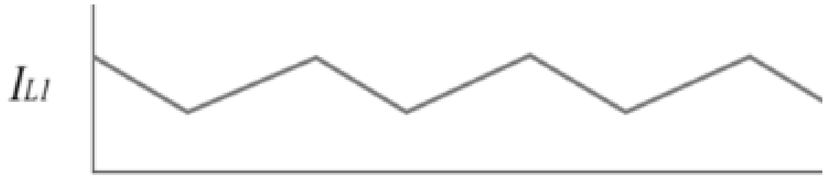
Coil is a resistance to AC but passes
through current when pulse is positive
Some current goes to load, rest
goes into setting up mag field

Field stores energy because of
this current

When pulse is at 0V, energy is
released from coil and continues
to load through lower diode and
energy from field

Current ripple pk –pk = Vout x pulse off-ti



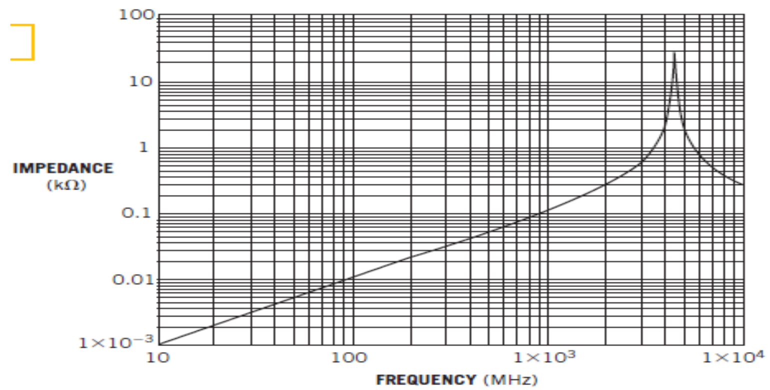


2. Resonance – another use of inductors

From before, a coil has a ‘resistance’ that increases with frequency and capacitors have a ‘resistance’ that decreases with frequency so if put in parallel you get a combination that gives a ‘resistance’ that rises to a peak value at a particular frequency then drops again. If put in series you get a ‘resistance’ that drops to a minimum value at a particular (resonant) frequency.
This can be use in electronics to select or deselect signals at the resonant frequency

F = 1/ (2 x Pi x SQRT(LC))

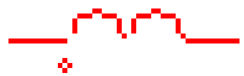
In practice coils have ‘self’ capacitance see later



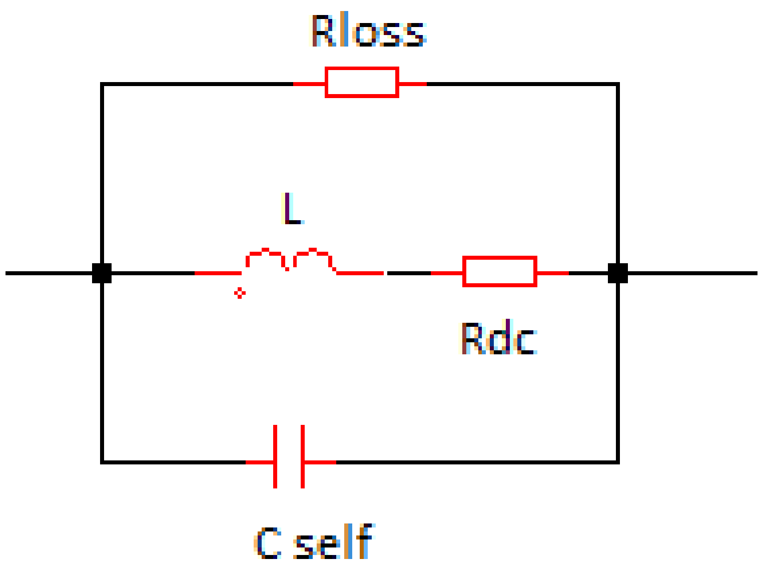
Magnetics basics

Practical electrical considerations

Ideal Inductor:



Real inductor has:



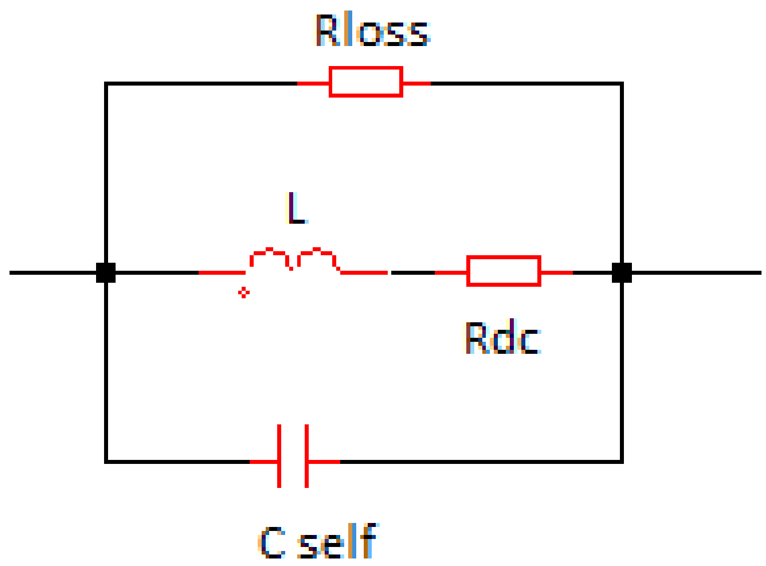
Ideal inductance L
DC resistance Rdc
Self capacitance Cself
Core losses Rloss

L, Rdc, Rloss all vary with frequency
Rloss also varies with drive level (flux der

Inductor core can also magnetically saturate where L goes to low value

Magnetics basics

Practical electrical considerations



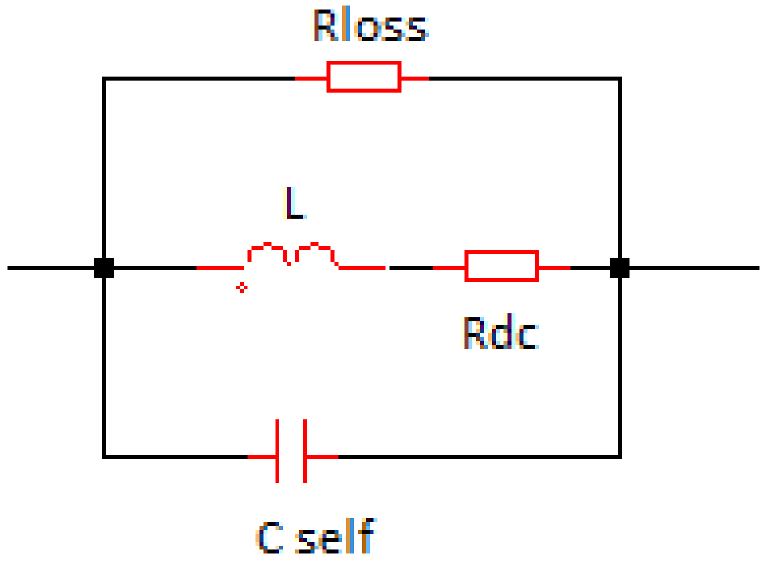
Rdc is the resistance of the winding and produces heat with increasing current which produces temperature rise which may be a limiting factor rather than saturation

Rdc does increase with frequency due to 'skin effect' as current crowds to the edges of the conductor as frequency increases

Eg at 100kHz, skin depth is ~0.2mm so 0.4 mm wire has no appreciable loss

Magnetics basics

Practical electrical considerations



Rloss is made up of three components

Hysteresis loss - due to the magnetic domains resisting change as flux changes (increases with frequency)

Eddy current loss - due to unwanted flux coupling with other surrounding metal or the core itself causing currents to flow and resistive losses

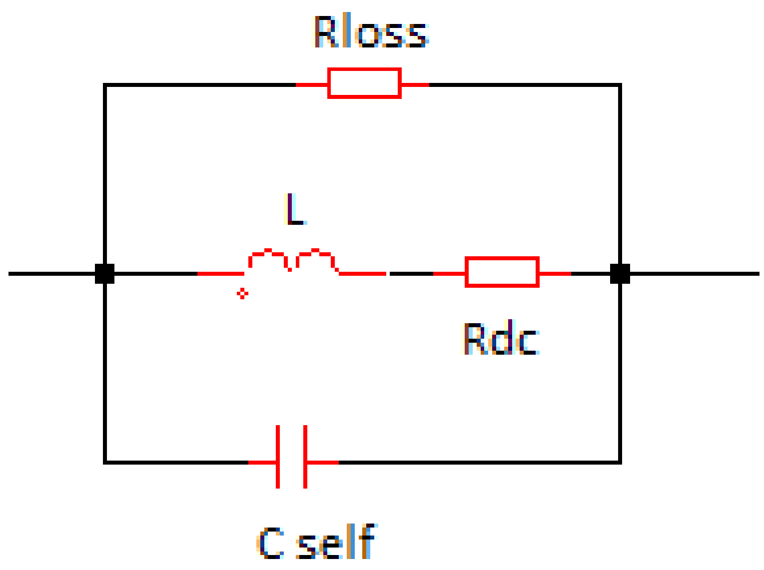
Other – Miscellaneous odd effects in the core

Magnetics basics

Practical electrical considerations

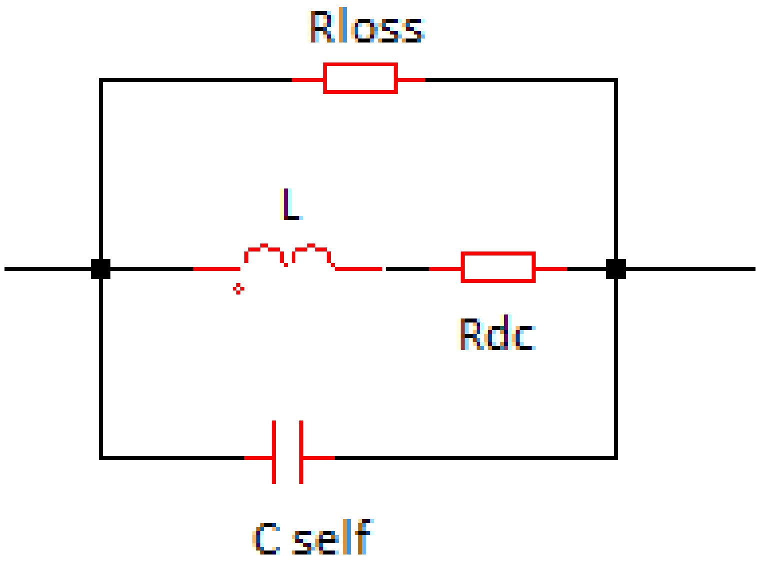
Cself is the distributed capacitance of the winding and causes self-resonance that could cause voltage overshoots when transient voltages or currents applied

At high frequencies, the core loses permeability and so is less able to add its own magnetic field to the inductor so the inductance falls



Practical electrical considerations

Voltage breakdown from turn
to turn and from start to finish can be an issue when the inductor see high pulsed voltages end to end. In NCL products this doesn’t normally occur but customer do use inductor this way



Eg non-isolated ‘buck’ converter off the mains

Gz has specialised test kit which applies high voltage pulses to look for breakdown

Magnetics basics

Practical electrical considerations

Magnetic Saturation

This is a phenomenon of the core material whereby it has aligned all of its internal 'magnetic domains' so that further increase in current produces no more magnetic field from the core. The field can increase in the air but at a much lower rate with increasing current.

Saturation is caused by current

Saturation is a local effect so one part of a core can be saturated and another not. Smallest area of core in magnetic path saturates first

Actually individual domains are always 'saturated' one way or another – core saturation occurs when they are all saturated one way

Magnetics basics

Practical electrical considerations

Magnetic Saturation cont…

Because cores saturate with domains progressively flipping into alignment, magnetisation cure is actually minute steps not smooth

Toroids saturate from the inner diameter first progressively to the outer so inherently a ‘soft’ saturation ie not sudden over a particular current Same effect in other cores but not so obvious

Different materials saturate at different rates with current. High permeability ferrites saturate suddenly, iron powder more slowly.

Magnetics basics

Practical electrical considerations

Magnetic Saturation cont…

Saturation is a core effect so a particular material has a saturation flux density independent of turns or inductance of the winding.

For a material, saturation does depend on temperature heavily – its level can halve at high temps typical 25V figure 400 mTeslas

Flux density given by B = Inductance x Current / (Turns x CSA)

For a pulse applied, I = E x T/L, rearranging: L = E x T/I
so substituting,

B = Volts x time / (Turns x CSA)

Magnetics basics

Practical electrical considerations

Magnetic Saturation cont…

This relationship B = V x T/ Ae x N is often used but only really applies to pulses from a voltage for a certain time that result in the current that does the saturating

V and T are what users actually apply so a VT or ET maximum before saturation for given inductor is useful. This is a value for a particular would inductor. Must remember that this only applies to costant voltage pulses

A measure of what actually sets up the field at a specific point along the magnetic path is magnetising force: H

H = Turns x Current / length of magnetic path (le)

Magnetics basics

Practical electrical considerations

Magnetic Saturation cont…

H is a measure of the strength of the cause of the magnetisation

B is a measure of what field density results, the effect of H, depending on the contribution of the core material permeability μ

Relationship simply $B = \mu H$

Bmax and μ are fixed for a particular core material so for <u>that core</u> there is a value of H that causes saturation B max

$H_{max} = N I / l_e$

Magnetics basics

Practical electrical considerations

Magnetic Saturation cont…

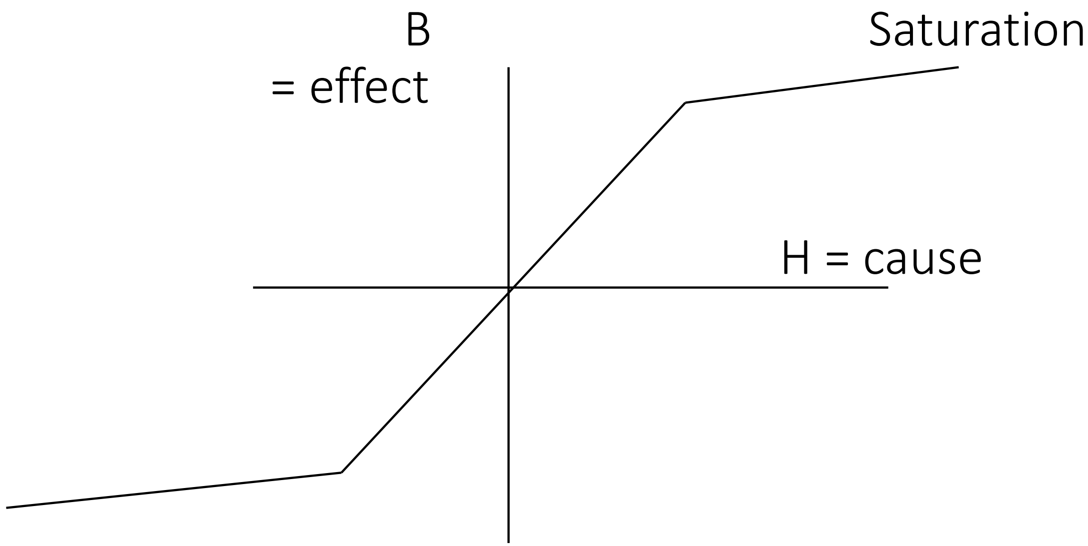
so H max at saturation doesn't depend on actual inductance value only NI and physical size of core so can say there is an Amp-turn limit for any particular core

Eg small drum core might have an Amp-turn limit of 80 before saturation

So can have 80 amps and 1 turn or 80 turns and 1 amp etc

Magnetics basics

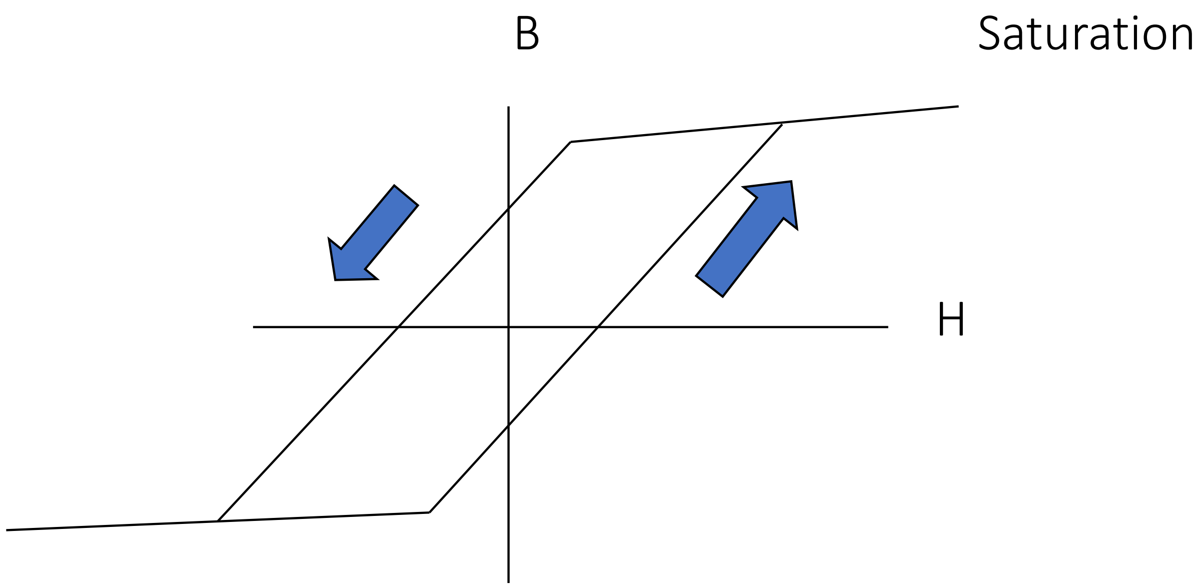
Can summarise the characteristics of a core material with its B-H curve. From before B = µ H where u is material permeability so nominally get:



A little like H = volts, B = amps, slope µ = resistance

Magnetics basics

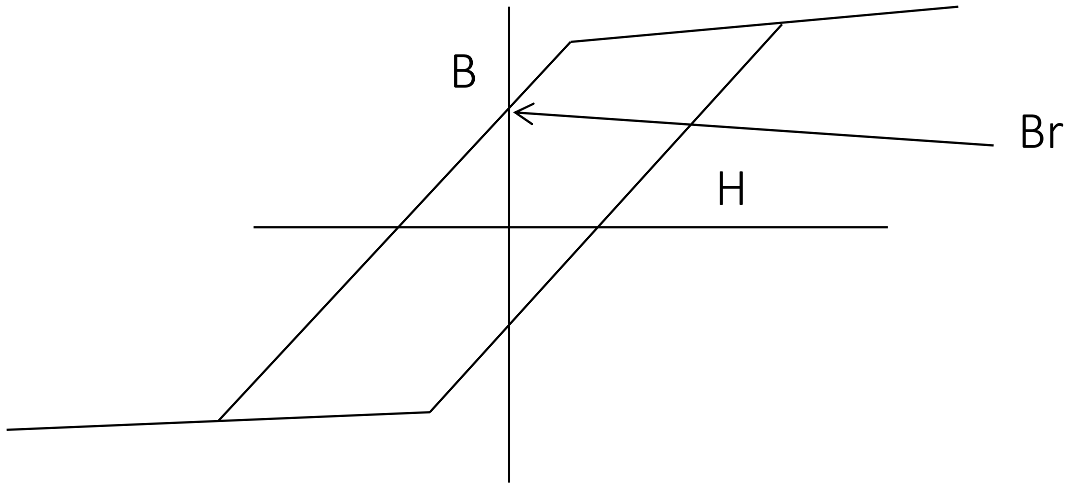
However, curve has 'hysteresis' due to 'stiction' of the magnetic domains.



Note corners are not really 'sharp' they can be quite rounded depending on material

Magnetics basics

Hysteresis

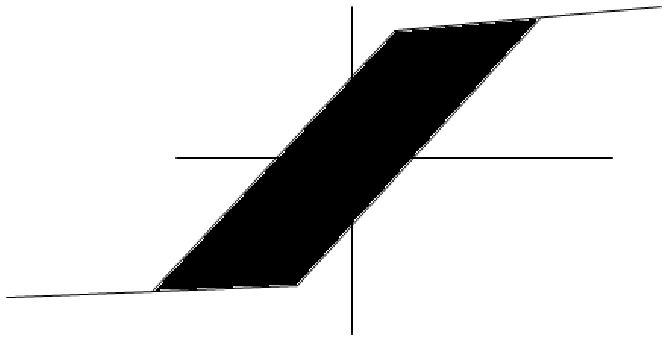


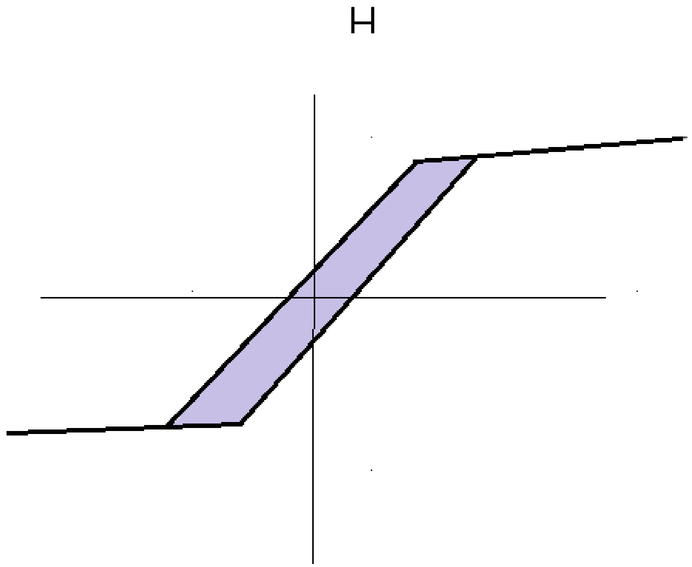
Point Br is the remanence point:
H (current) has gone to zero but B is still a positive value
Represents residual magnetism left in the core

If H (current) starts again from this point, there is a shorter path to saturation than if B had started from zero so it will take less
'E-T' or 'L-I' to reach saturation

Magnetics basics

Area inside the loop is a measure of the 'hysteresis' losses of the core

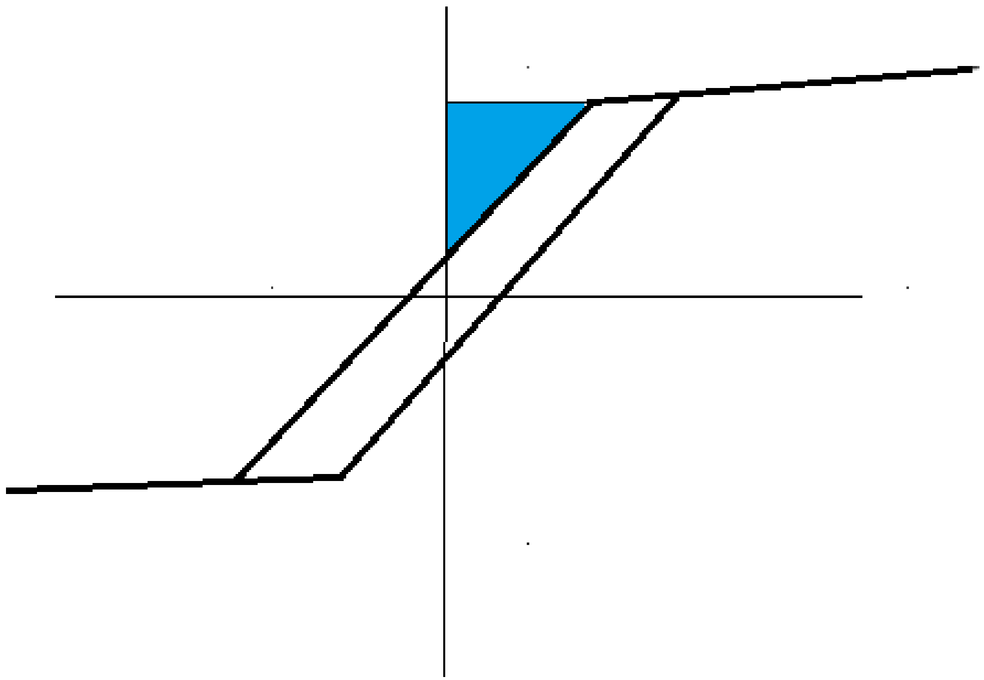




High Loss
(but suitable for a permanent magnet)

Low Loss

Area between the loop and the B axis is a measure of energy stored and released as the loop is traversed



Gaps

Why? – Reduces susceptibility to saturation with DC through the core Nominally doesn't reduce susceptibility to AC component

How? – Even a small gap increases total reluctance (magnetic resistance) of the core (think of high resistance in series with low resistance) Very little field intensity occurs in the ferrite, most of it is in the gap. Air cannot saturate so the DC through the winding can now increase greatly without saturating the ferrite

The effective permeability of the core assembly reduces (opposite of reluctance) so AL goes down and inductance goes down for given core set. So add more turns to bring inductance back to same value
but….. B = Inductance x Current / (Turns x CSA)
so if inductance now same with more turns, B has gone down

Gaps

Why not just reduce inductance or current or increase core size to reduce saturation?

Circuit may require this inductance value to work
Current may be fixed by the circuit
Bigger core size may not be feasible

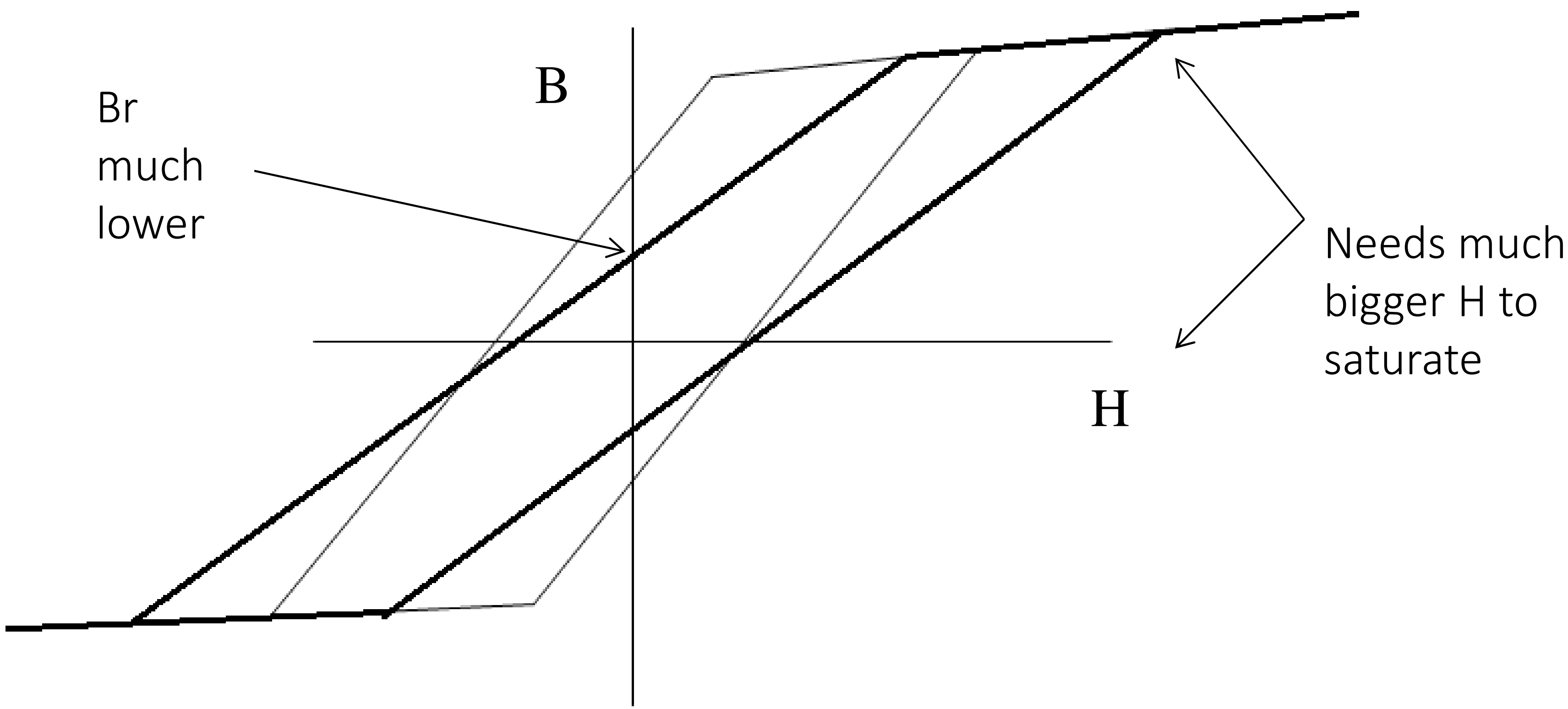
So add gap – permeability decreases so inductance per turn (AL) decreases

Need to add more turns to bring back inductance but…

Inductance proportional to turns squared so not so many extra turns required

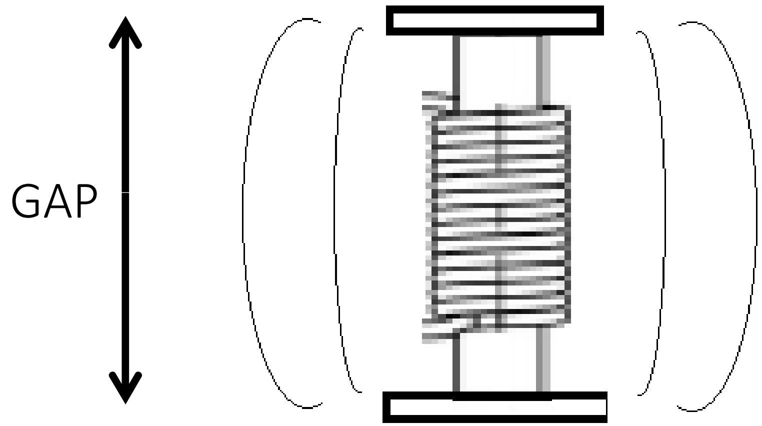
Gaps

Effect on hysteresis curve:



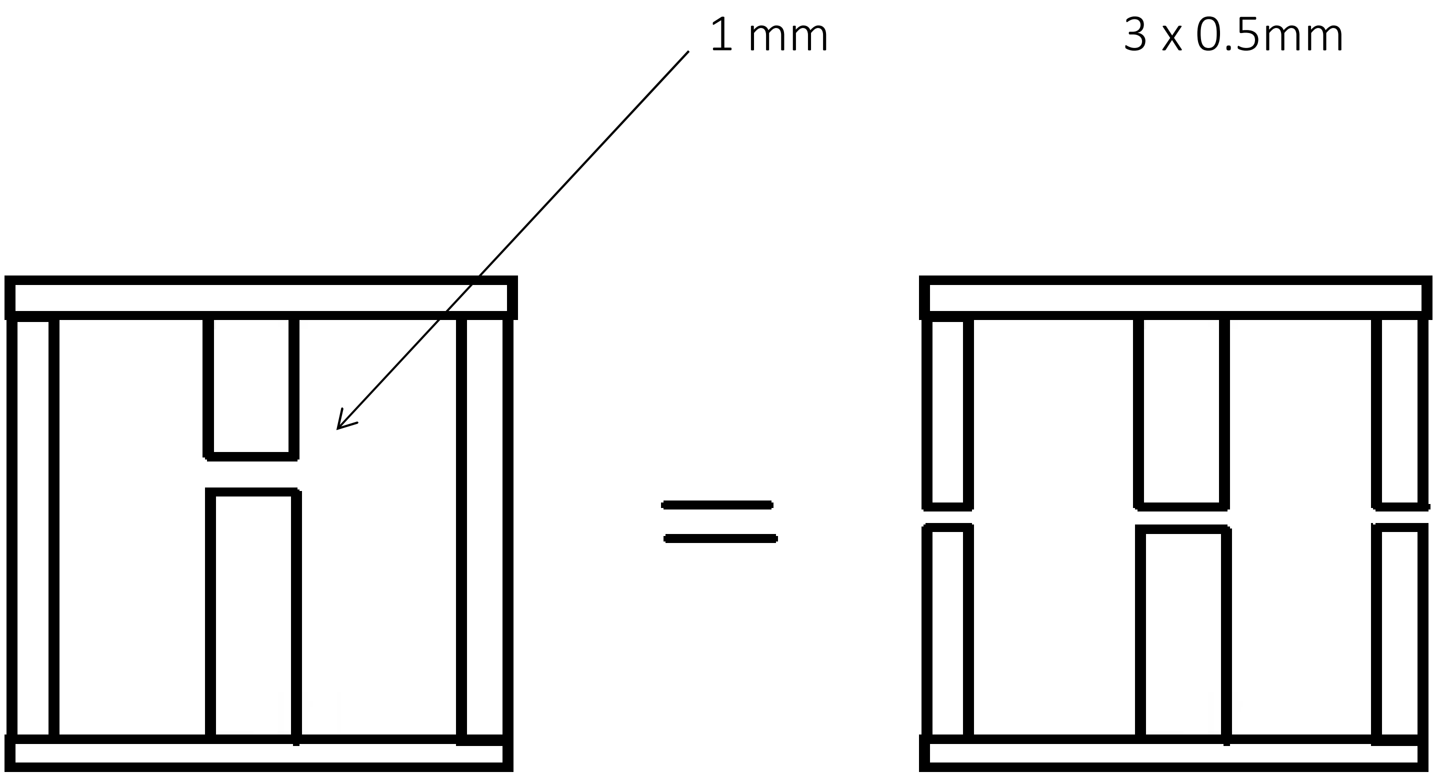
Gaps

Rod cores, drum cores and shielded drum cores always effectively have gaps in the magnetic path round the outside of the part – can't easily change



Gaps

E Cores can have a single gap in the centre limb or a gap in each outer limb. For same AL value, gap in each outer limb = ½ gap in centre limb



Gaps

Gap in centre limb makes part easier to assemble and contains leakage field round the gap within the winding

But – field in the winding causes ‘eddy current’ losses so outer limb gaps can cause less loss.

Gap can be calculated see (reference sheet) but equation gets less accurate for large gaps so often suppliers are asked to test gaps and supply parts with specified AL value

Toroids (and E cores less often) can have distributed gaps by mixing ferrite with non-magnetic material. The filler (typically resin) does produce additional losses though

Gaps

For E cores with centre limb gap useful to use one ungapped core and one gapped. Reduces cost but increases risk of mis-assembly ie 3 combinations possible

Usually make outer limb gaps with spacers – note if you want say 1mm gap – need 0.5mm spacers in each outer limb so each magnetic path has 1mm total

Center limb gapped cores can be glued together at outer limbs. Outer limb gapped cores have to have tape or clips to hold cores together

Gaps

Gap can be calculated from Inductance required, turns and CSA of the core

$$l_g = \frac{\mu_0 \mu_r N^2 A_e . 10^3}{L}$$

This is quite accurate when the gap is a small proportion of the overall magnetic path length. Otherwise can 'suck and see' or ask supplier to grind the gap to give a particular inductance with particular turns eg grind to a particular AL value

Magnetics basics

$$B = {}^{VT}\!/_{A_e N} \qquad B = {}^{LI}\!/_{A_e N}$$

$$E = \frac{1}{2} L I^2 \qquad L = \frac{\mu_e \mu_0 N^2 A_e .10^3}{l_e}$$

$$V = -L \frac{dI}{dT} \qquad H = \frac{4\pi N I}{l_e}$$

$$A_L = \frac{nH}{T^2} \qquad l_g = \frac{\mu_0 \mu_r N^2 A_e .10^3}{L}$$

$$\mu_0 = 4\pi.10^{-7} \qquad \Delta = \frac{66}{\sqrt{f}}$$

$$B = \mu H \qquad \mu_e = \frac{\mu_i}{1 + \frac{l_g \mu_i}{l_e}}$$

Where B = Flux density (Tesla)

L = Inductance (μH)

I = Current (Amps)

T = Time (μs)

Ae = Core cross sectional area (mm^2)

V = Voltage applied (V)

N = Turns

E = Energy (μJoules)

nH = nanoHenries

A_L = Inductance factor for a core

l_g = gap length (mm)

μ_r = relative permeability of the material (gap = 1)

μ_i = initial permeability

μ_0 = permeability of a vacuum

H = magnetising force (Oersteds)

l_e = magnetic length (mm)

Δ = penetration (skin) depth (mm)

f = frequency (Hz)