Short Circuit Design Considerations

Transformer Concepts & Applications Seminar

Goldsboro, NC

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Kayland Adams joined Prolec GE Waukesha in 2017. He has been designing medium power production order transformers with ratings up to 75 MVA, 230kV class, 900kV BIL. Kayland holds a Bachelor of Science Degree in Engineering with Mechanical concentration from East Carolina University.

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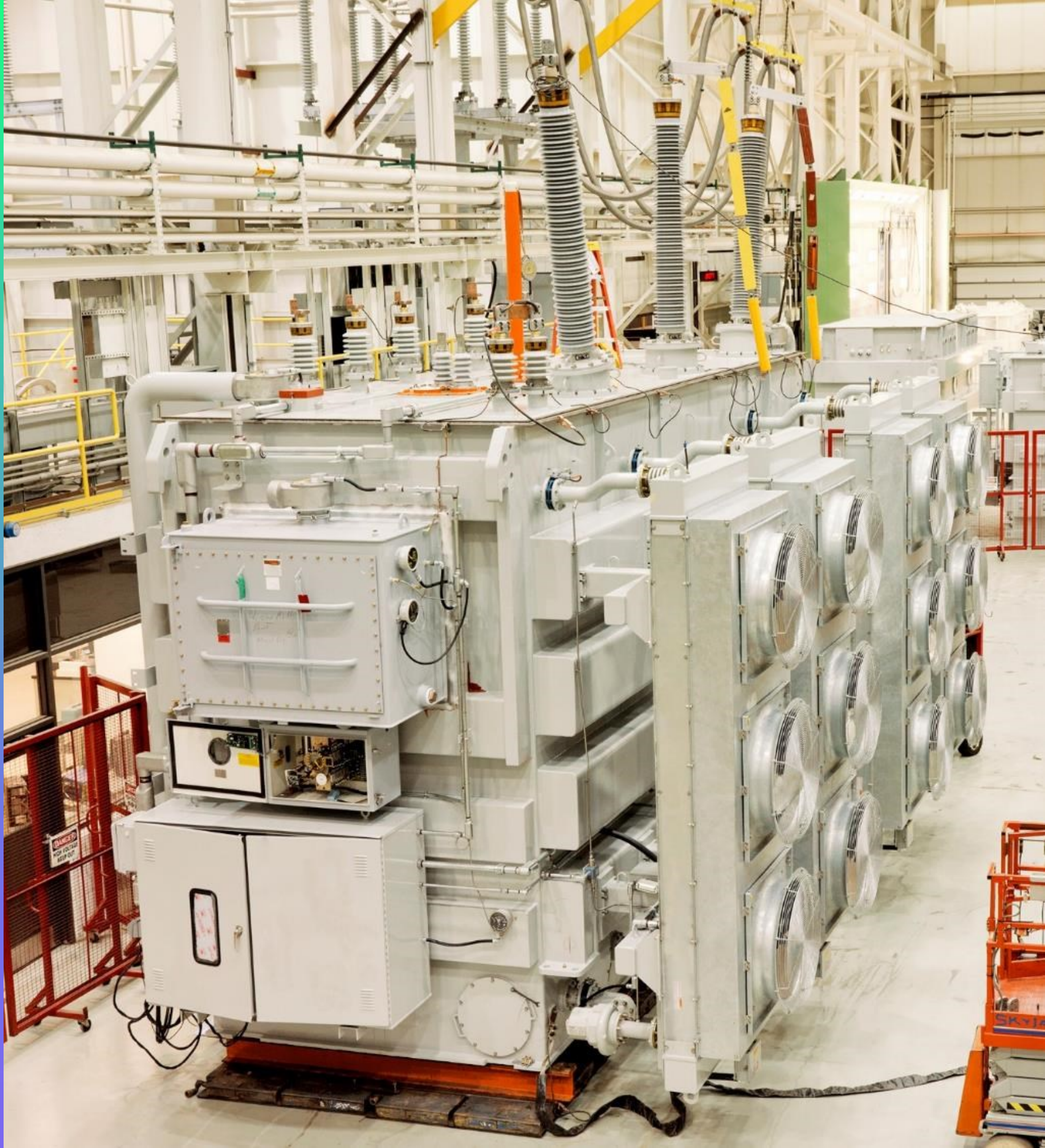

Agenda

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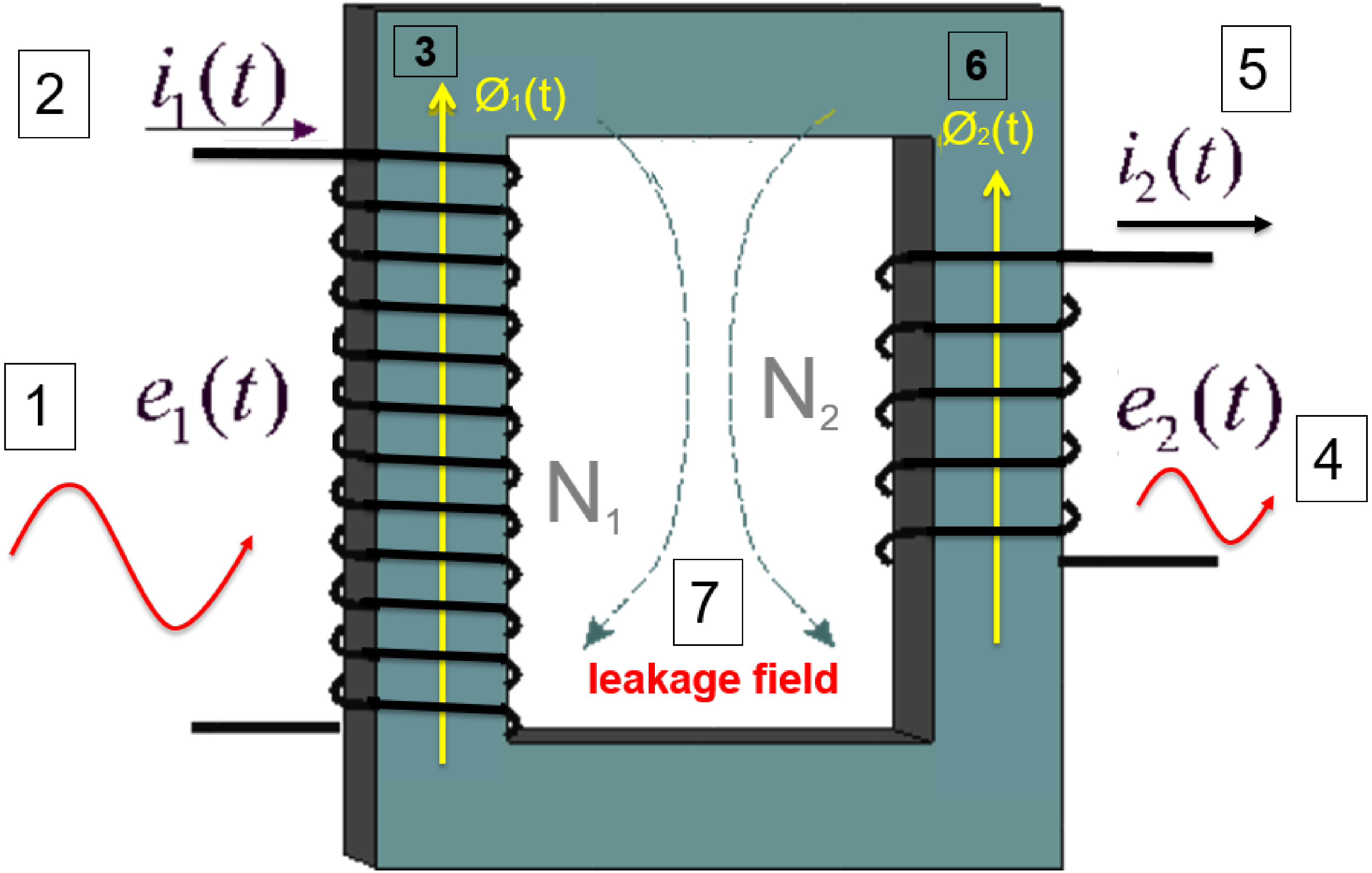
- Review transformers: How they work (textbook vs reality)
- Visualize relationship between Current and Magnetic Forces
- Understand fault current from time t = 0 to t = ?
- Understand formulas and variables to calculate short circuit currents
- Discuss fault types
- Calculation Example: Calculate short circuit amps

★Get a mental picture of magnetic forces acting within a transformer resulting from short circuit

Part 1: Transformer Basics:

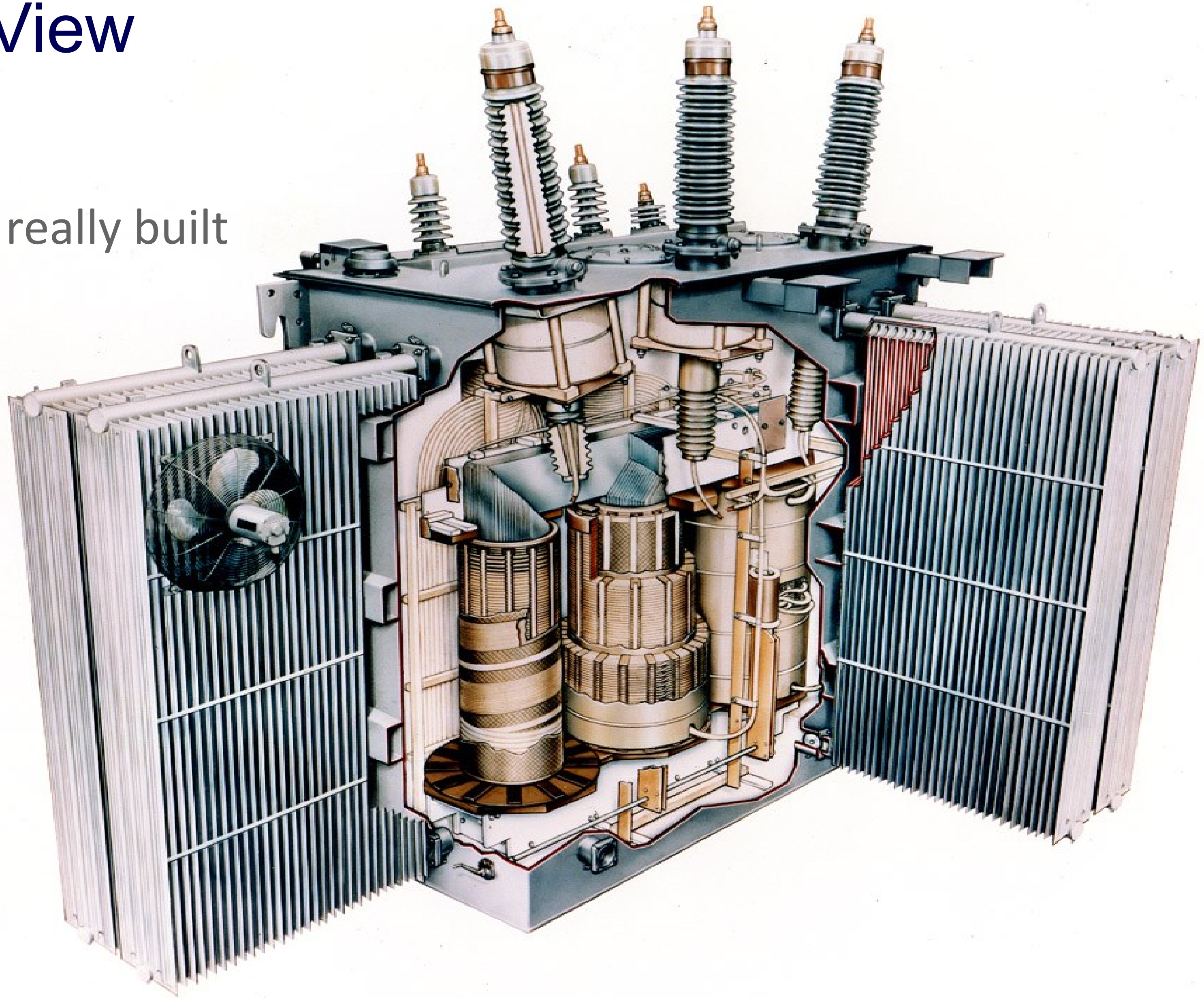
- How they work
- How they are actually built

Textbook Transformer (step by step)

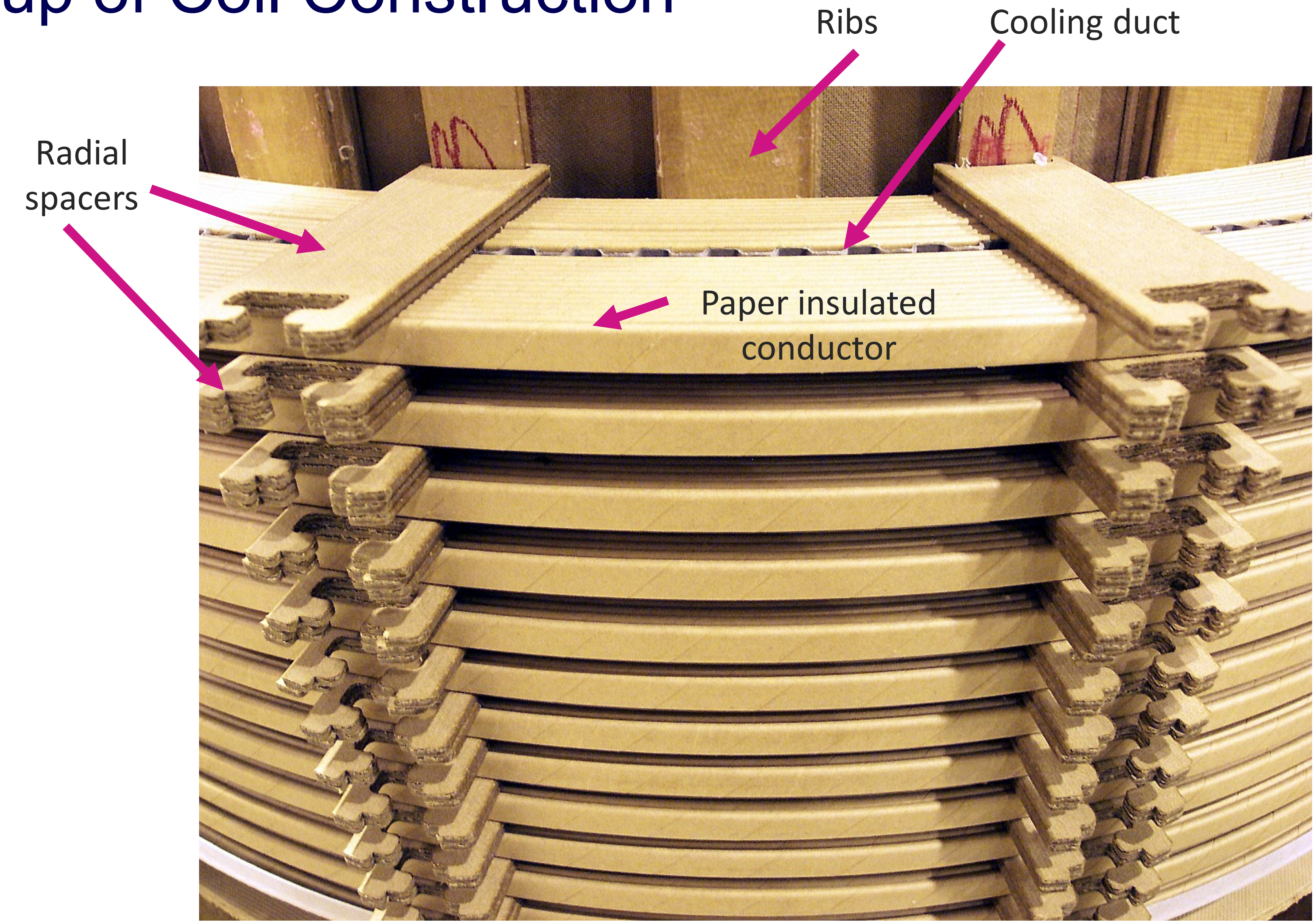


Cutaway View

How they are really built



Close up of Coil Construction

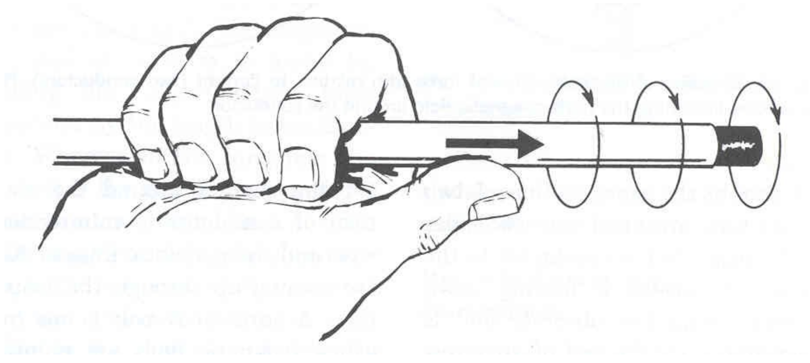


Fundamentals of Magnetics and Forces:

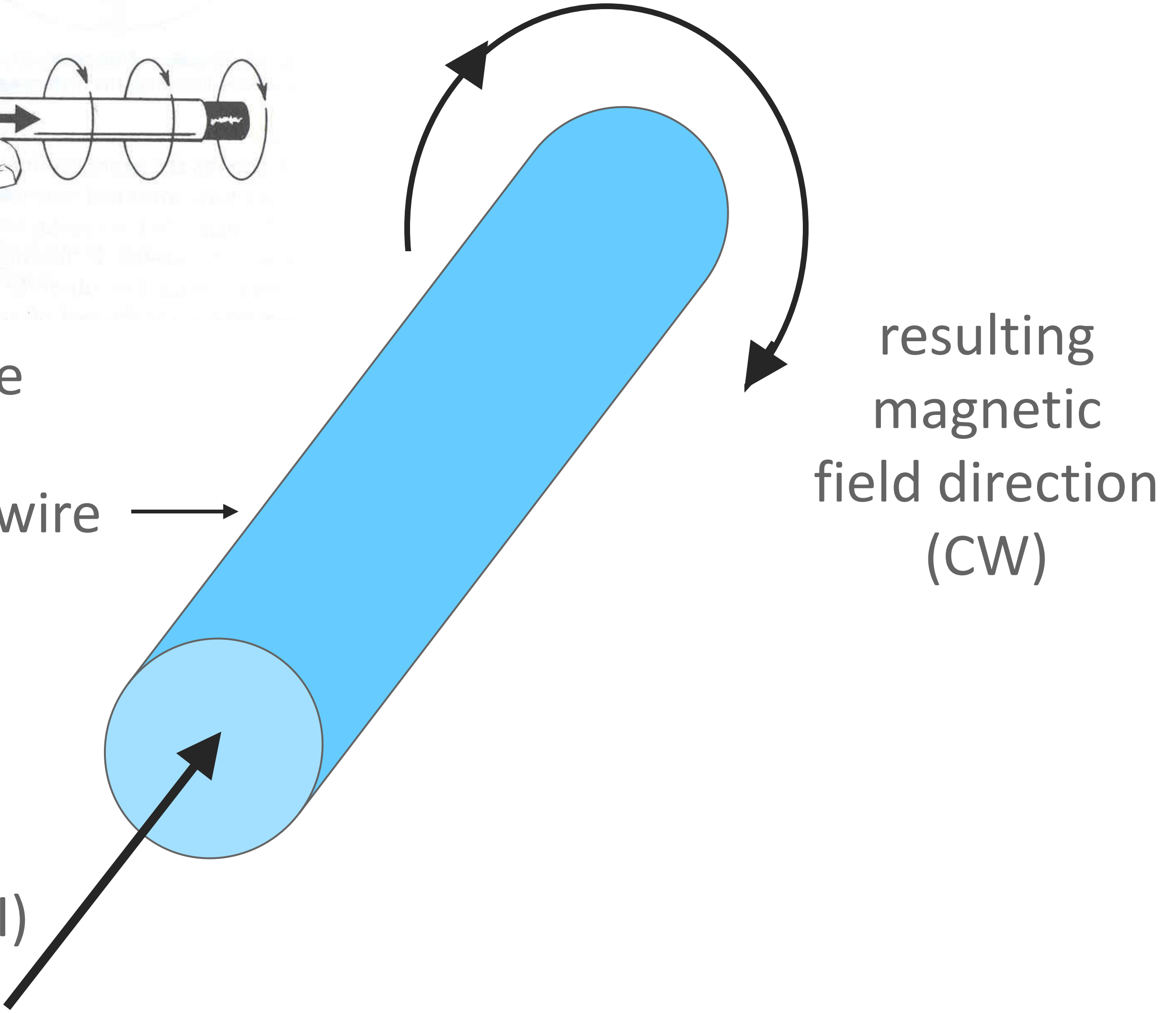
Magnetic Fields Around Conductors

Forces That Result

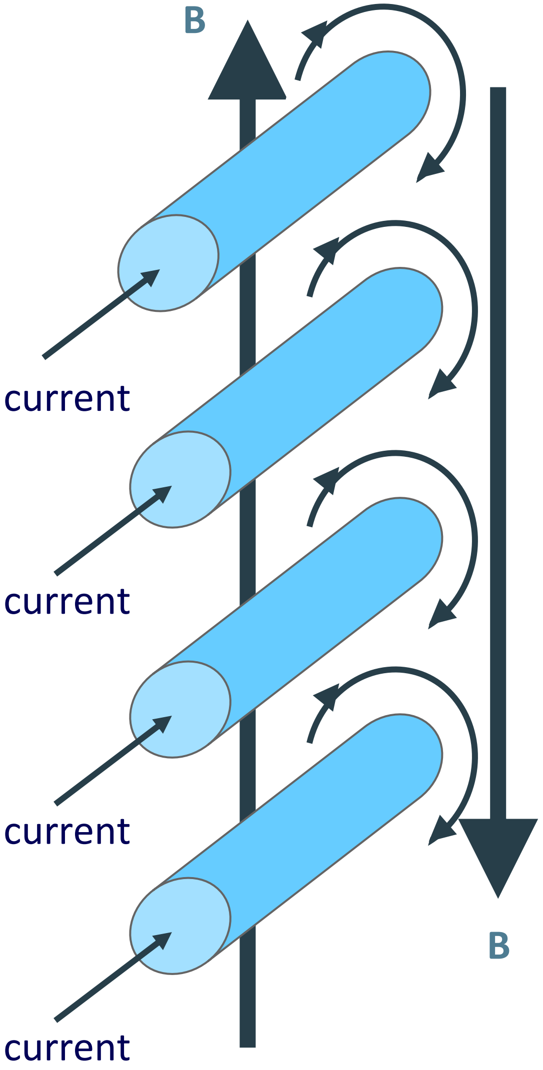
Current & Magnetic Field Relationships

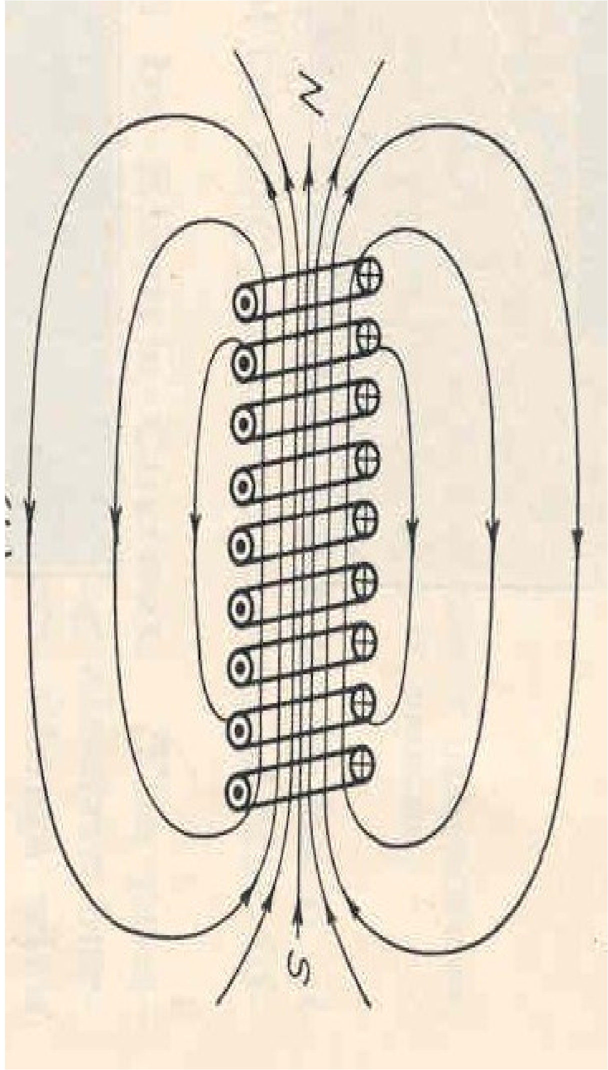


Right hand rule



Effect of Many Turns

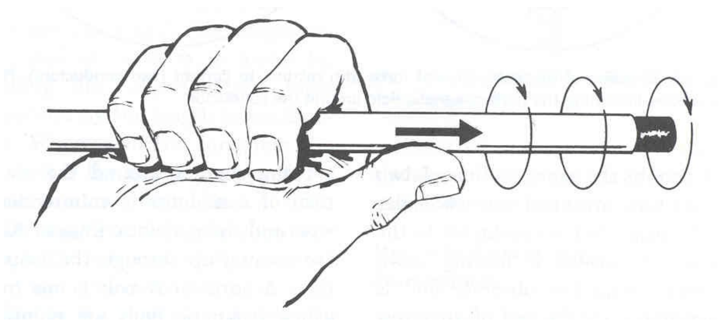




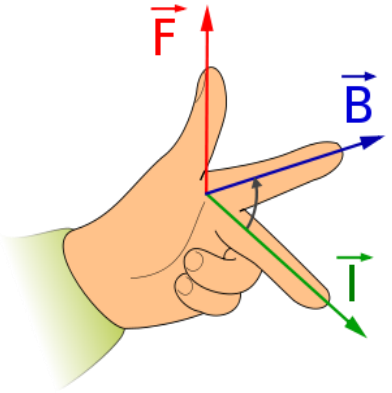
- Fields at inner/outer edges add together.
- One uniform magnetic path results
- Magnetic field (B) intensifies with # turns (N) or the current (I).

$$B \propto NI$$

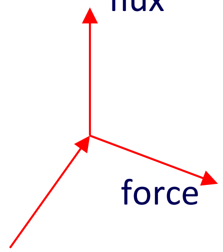
Leakage Field / Current / Force Relationships

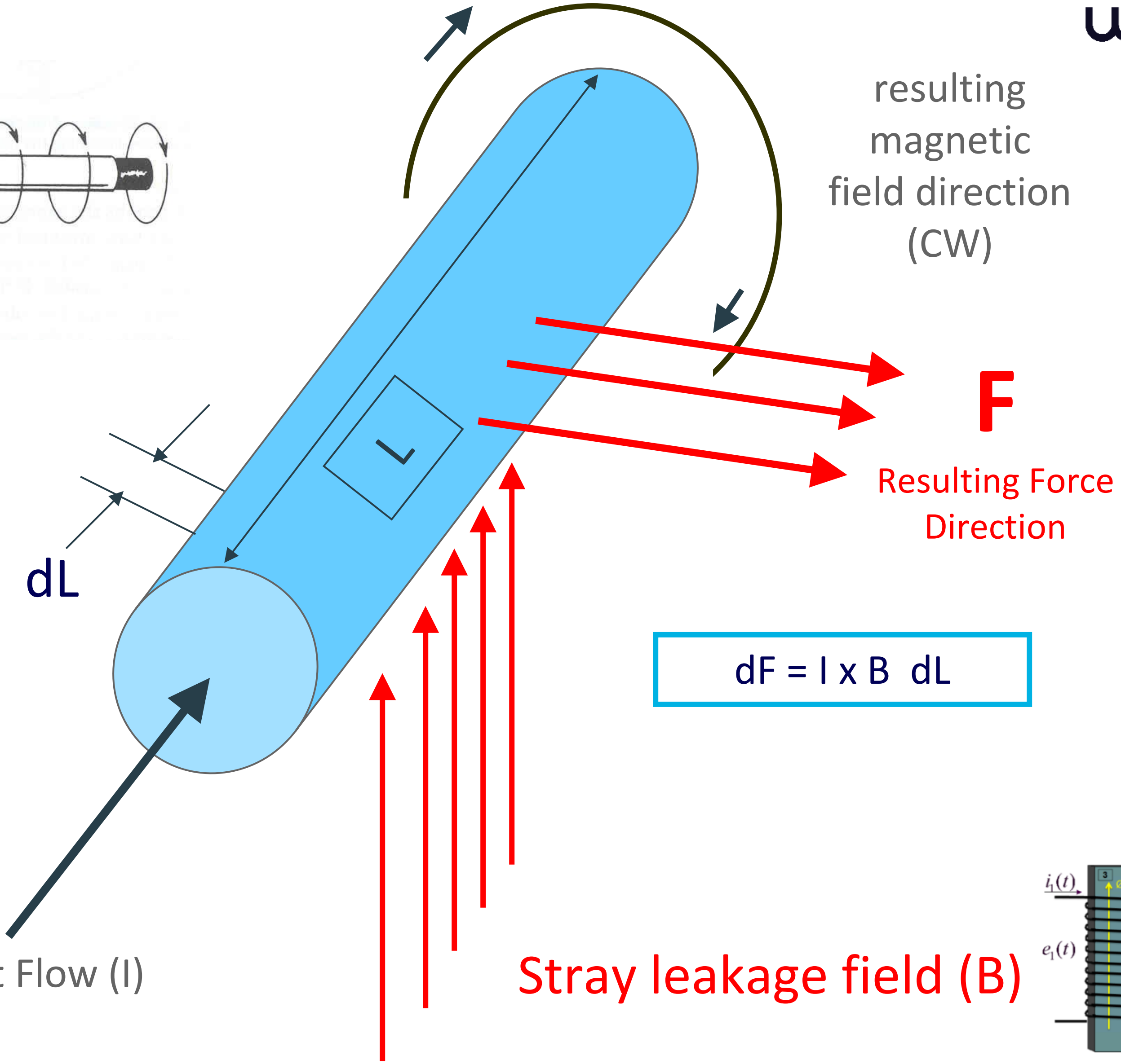


Right hand rule

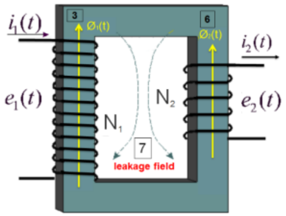


Left hand rule

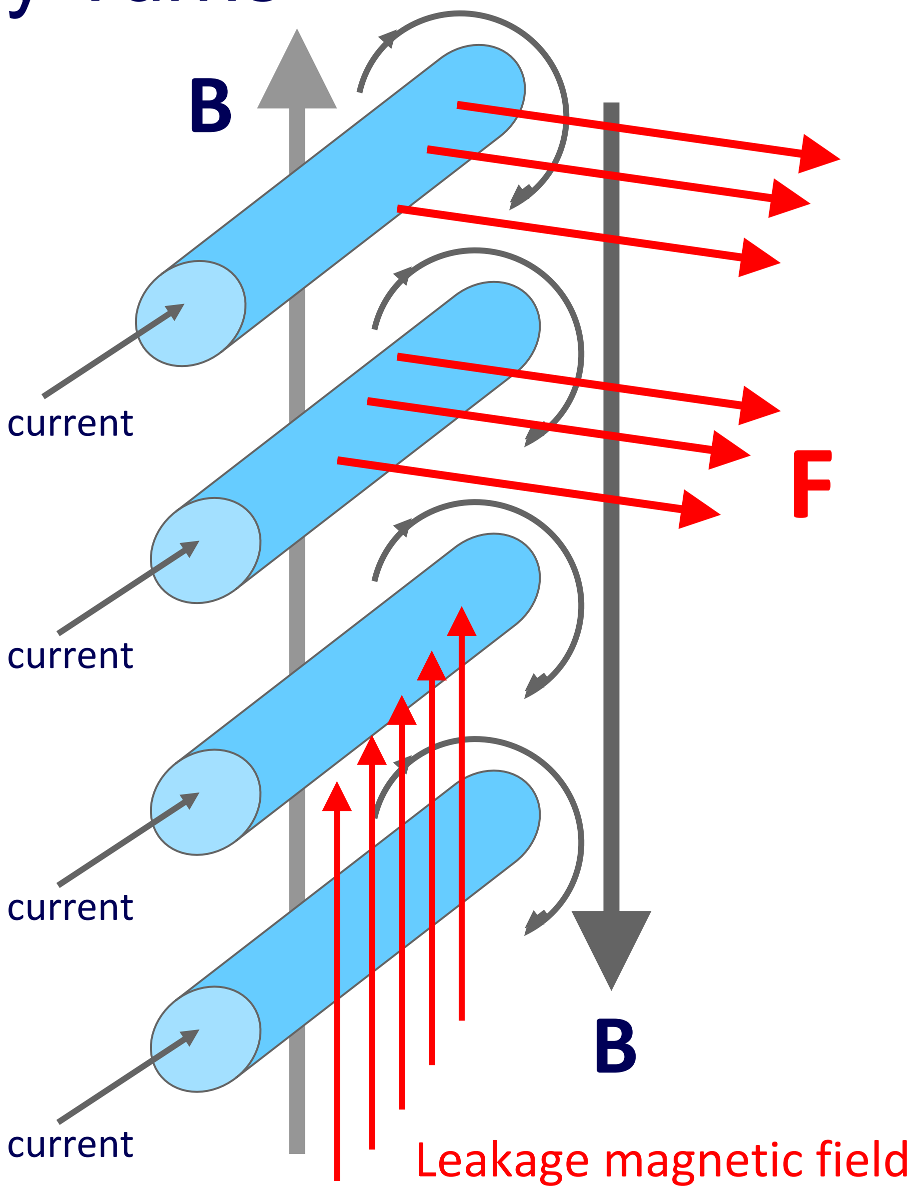




$dF = I \times B \; dL$



Effect of Many Turns



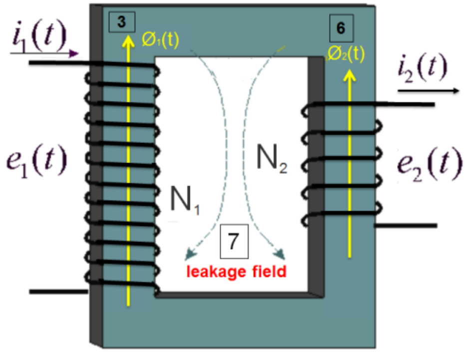
- Fields at inner/outer edges add together
- One uniform magnetic path results
- Magnetic Forces (F) intensifies with # turns (N)

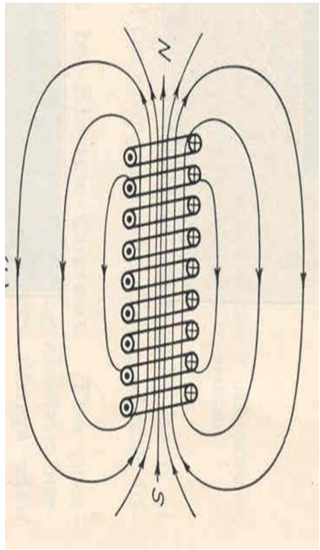
$$B \propto NI$$

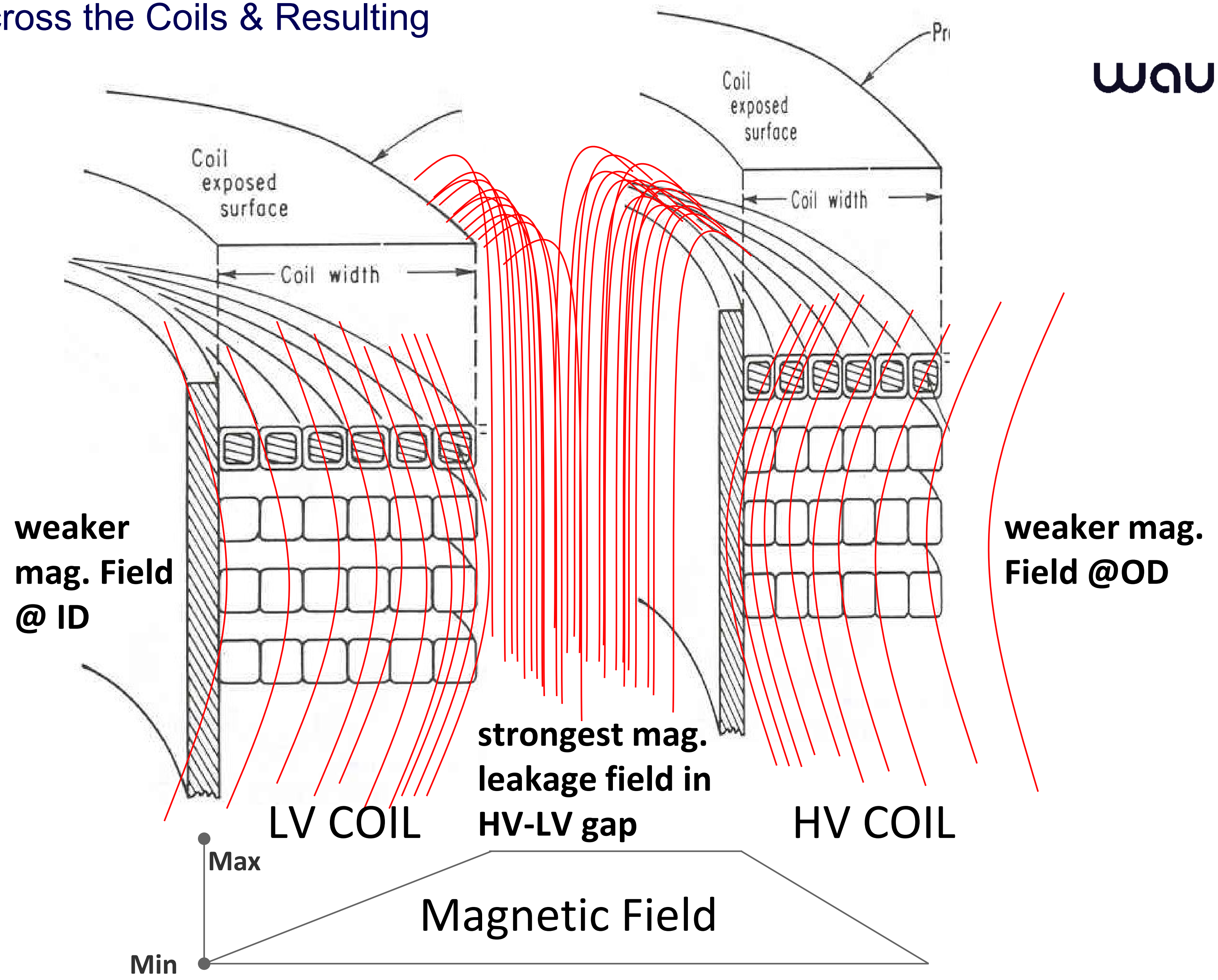
$$dF = NI \times B\, dL$$

$$F \propto (NI)^2$$

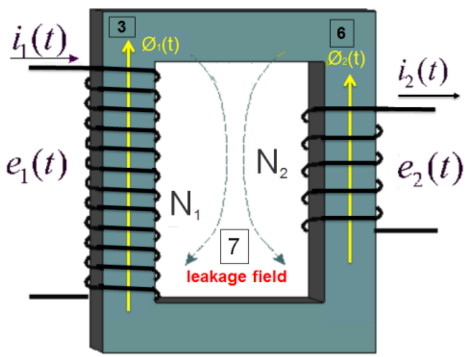
Magnetic "Leakage" Field Across the Coils & Resulting Forces

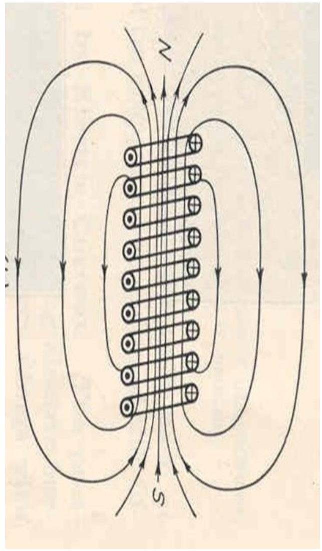


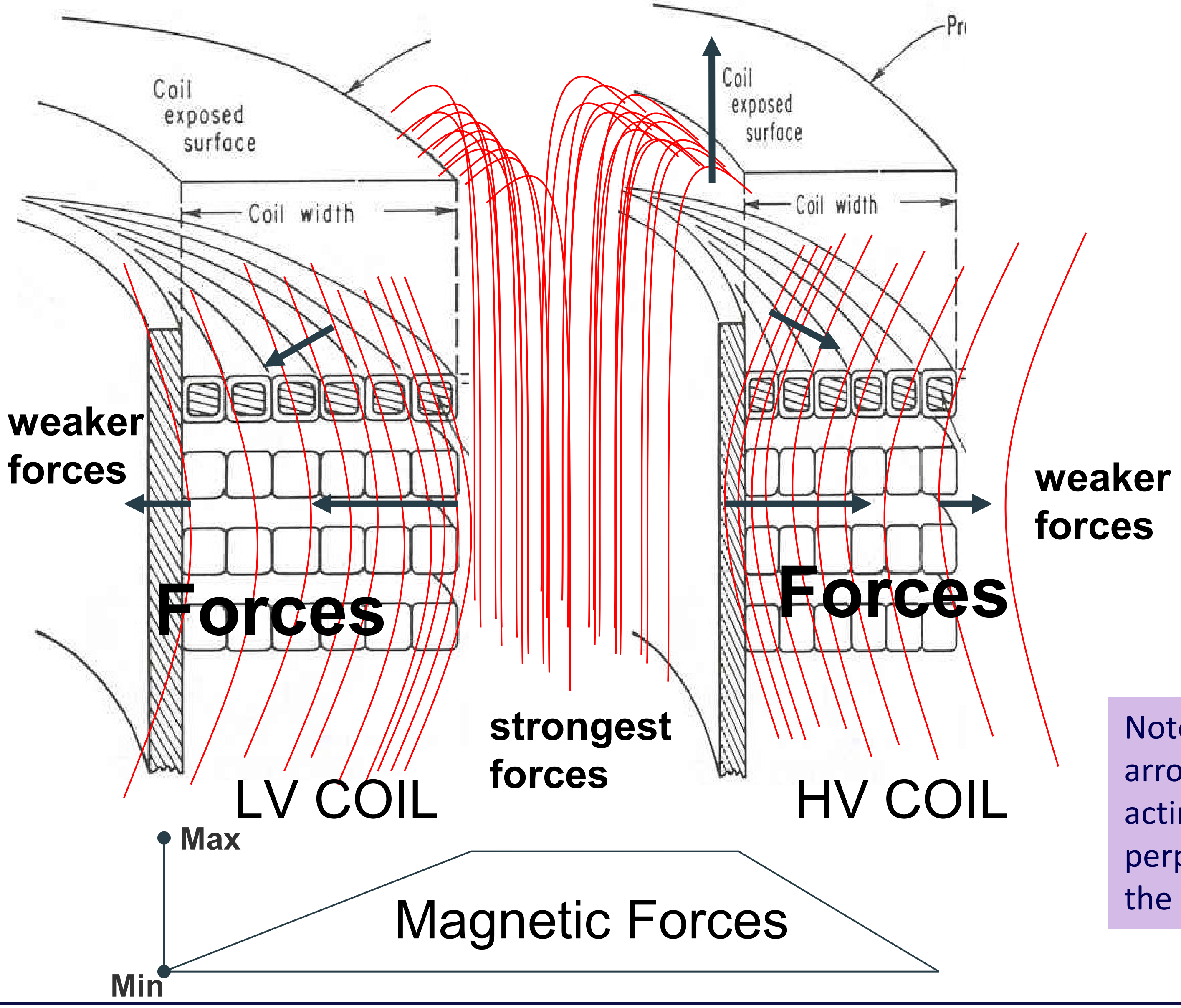




Magnetic Forces Across the Coils

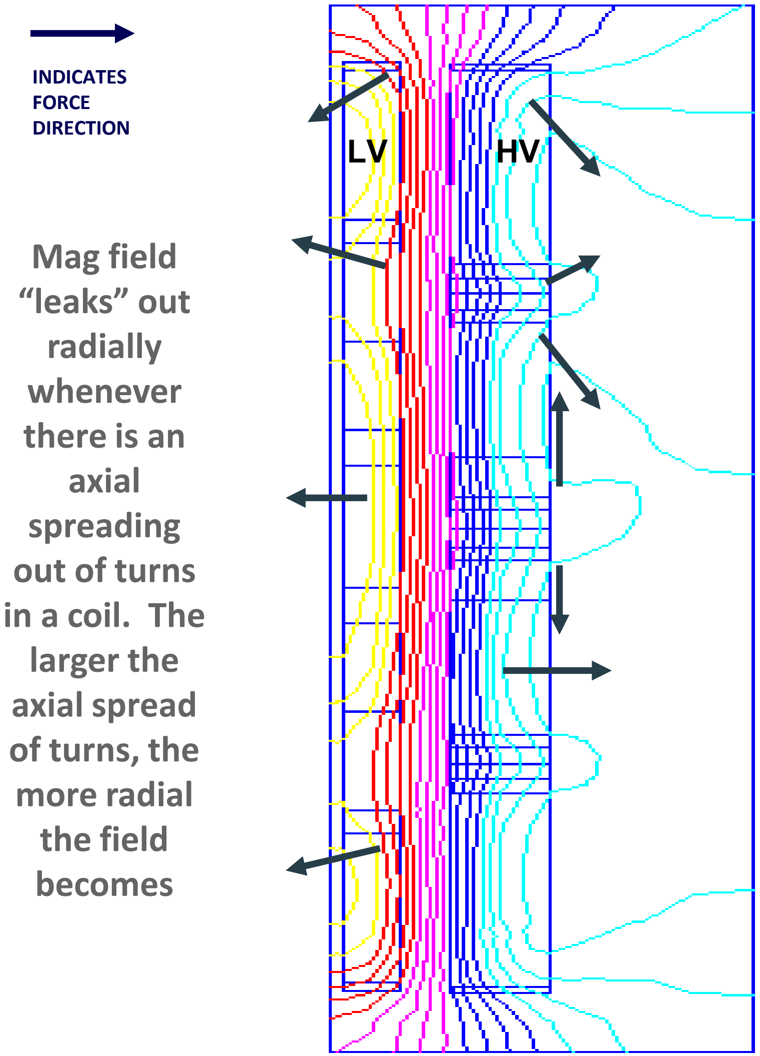






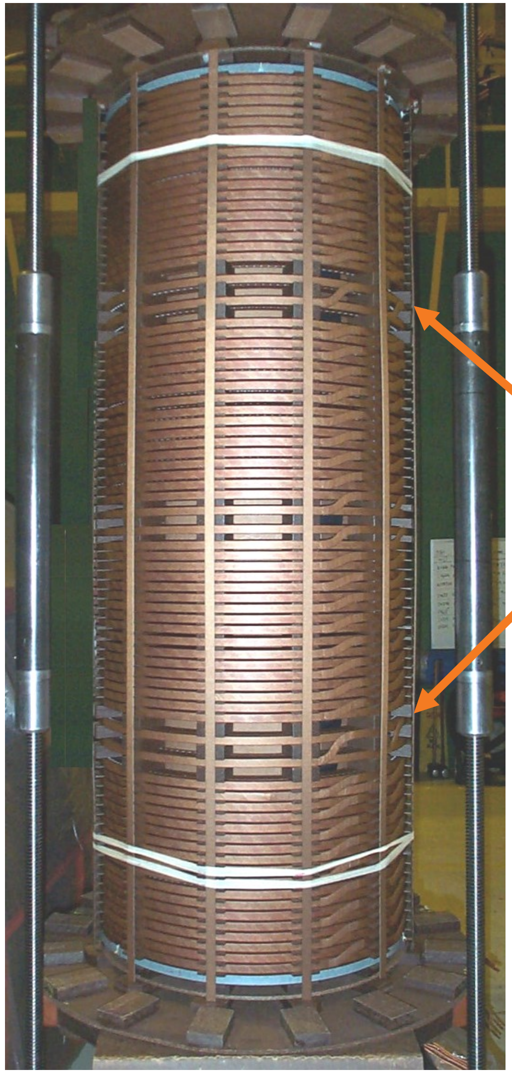
Note the force arrows are acting in 3-D and perpendicular to the mag fields

FEA field plot



Mag field "leaks" out radially whenever there is an axial spreading out of turns in a coil. The larger the axial spread of turns, the more radial the field becomes

Finite Element Analysis of Leakage Field Between Coils



Axial locations of where HV DETC taps are located

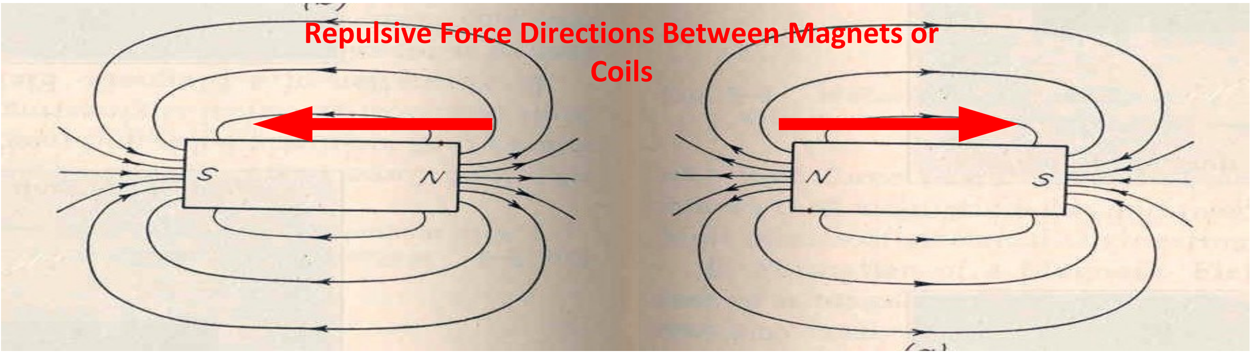
Note the force arrows are acting in 3-D and perpendicular to the mag fields

Summary of what we discussed so far…

- Magnetic forces are produced whenever
  - You have current flowing thru a conductor, and
  - A leakage magnetic field also passes thru the conductor.
  - Resulting forces have a direction of 90 degrees to the direction of current through the conductor versus the direction of the leakage magnetic field around the conductor (left hand rule)
  - The leakage magnetic fields can pass thru conductors at any angle (3 dimensional)
  - Forces then are also 3 dimensional in nature

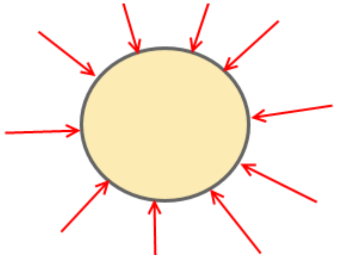
Magnetic Forces

- A net magnetic force also results between two coils (i.e. HV to LV), because the two coils are essentially two huge electro-magnets that repel each other.



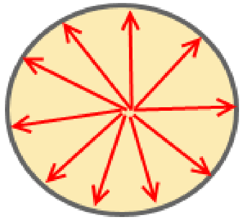
Cumulative force between these coils could be millions of pounds

- The inner coil experiences net inward radial "crushing" compressive forces



LV coil

- The outer coil experiences net outward radial expanding type forces



HV coil

Part 3: Short Circuits (Faults):

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What are they?

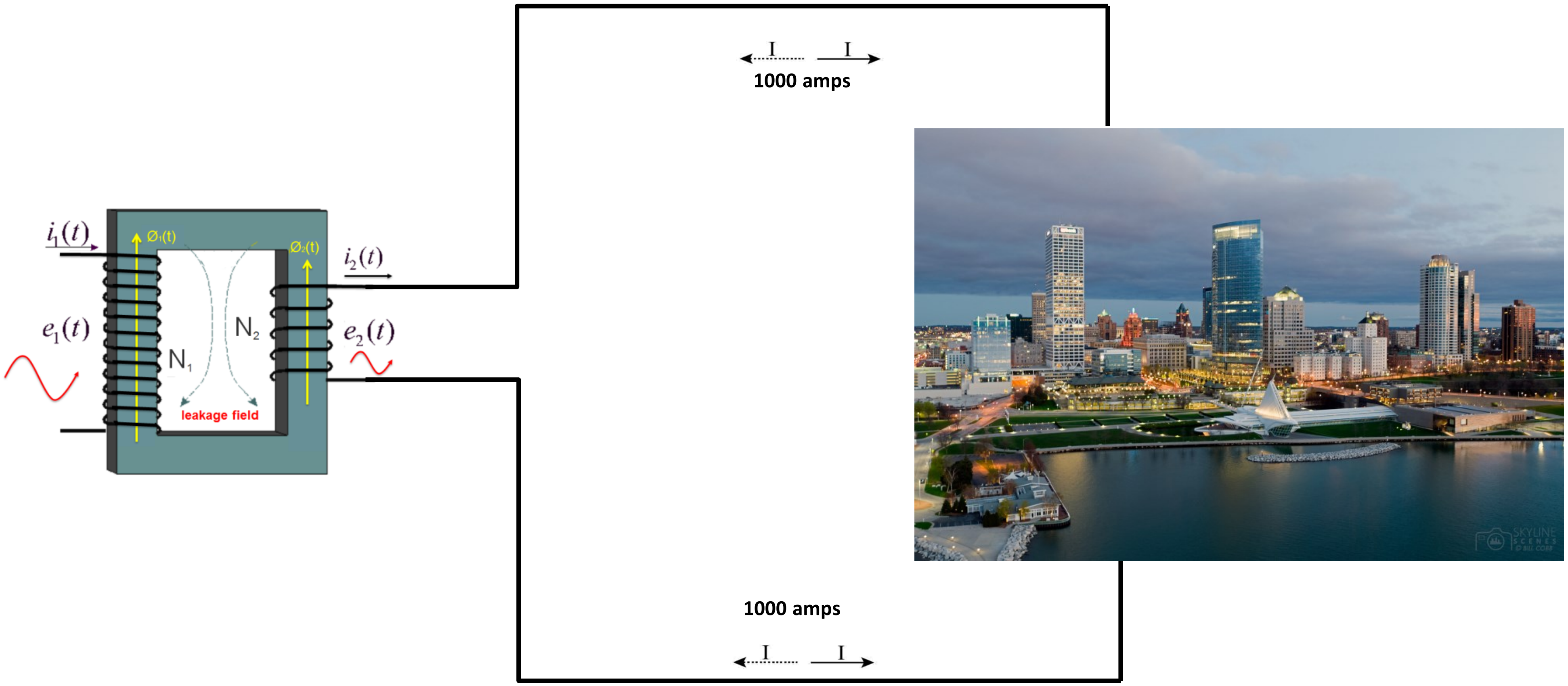
How do they happen?

What do they do to my transformer?

Normal Transformer Operation

Normal Circuit

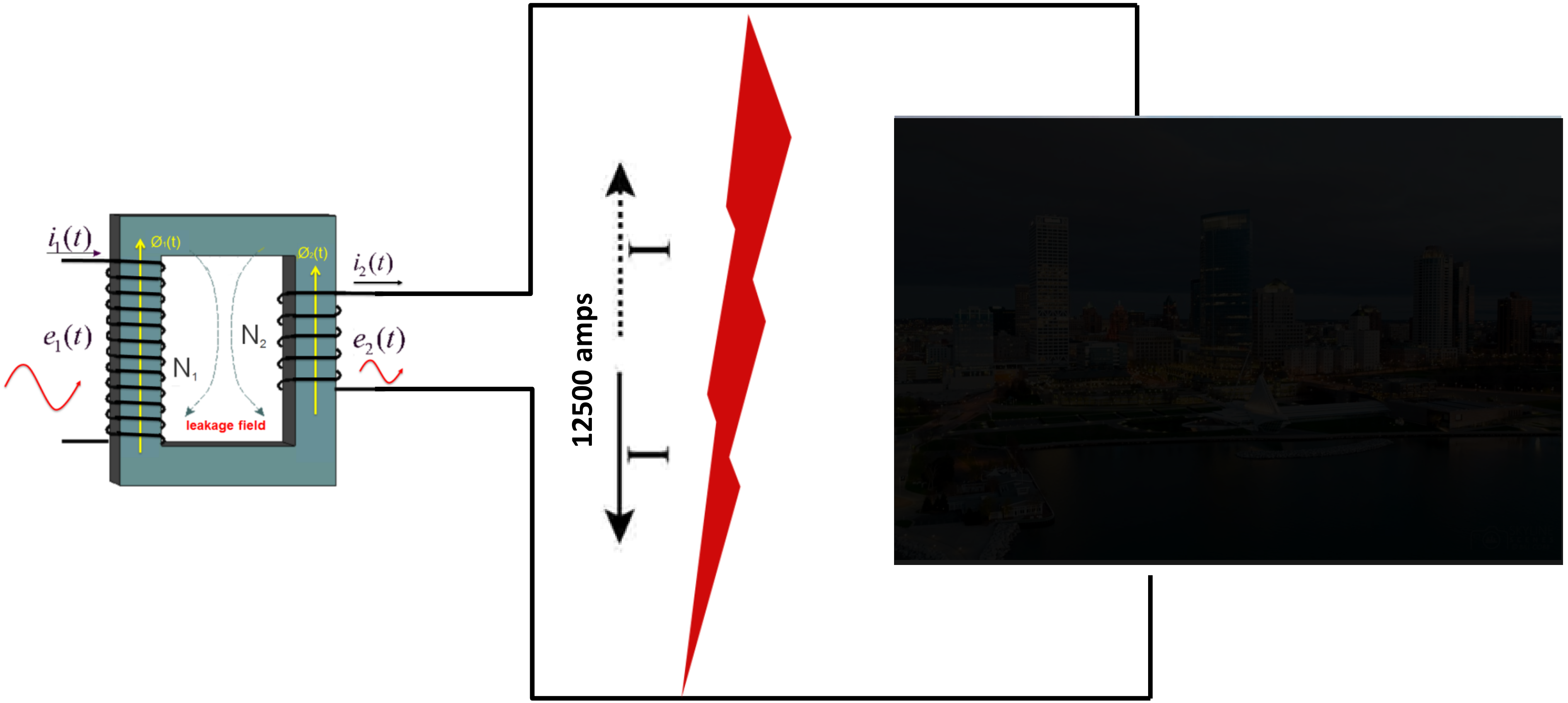
- An AC source supplies power to a given load (i.e. a city). A complete circuit has a source, with power entering a load and returning to the source. Amount of current that flows is directly related to the load on the transformer.



What is a Fault?

System Fault

- An un-intended “electrical connection” made between two energized components having different voltage potentials.
- Results in some (or all) of the current bypassing the intended load.
- Currents are typically very high due to low “fault impedance”



Types of Faults (and how they happen)

Basic Types of Faults in Power Systems

- Line-to-Ground (Most Common)
  - One or more conductors make “electrical” contact to ground
  - Example: Wildlife or Lightning. A lightning strike hits a line, then causes a flashover. The stroke between the line and ground causes ionization of the air (a conductive channel path to ground).

Lightning can reach 100 million to 1 billion volts, and generate up to a billion watts of power

Types of Faults *(cont.)*

Basic Types of Faults in Power Systems

- Line-to-Line
  - Two different phases come into direct or indirect contact with each other
  - Example: A bird with a large wingspan touches two conductors simultaneously and creates a conductive path between the two lines

Types of Faults *(cont.)*

Basic Types of Faults in Power Systems

- Double Line-to-ground
- Three Phase (least common)
  - Similar to Line-to-Line but when all three
    phases make contact with each other
  - Example: A falling tree
    on a transmission line creates a conductive path between all 3 lines and to ground

Designing For Short Circuit

Section 7 of IEEE C57.12.00 addresses design requirements for short circuit

- Fault current magnitudes and their behavior over time (time durations, wave shapes, etc.).
- Temperature limits of winding conductor after a fault
- Power system impedance that may be used to help limit fault current
- Short circuit test methods and how to analyze, inspect, etc.

Example of How to Calculate SC Current

C57.12.00 Section 7 defines both symmetrical and asymmetrical current

Symmetrical Current

$$I_{SC} = \frac{I_R}{Z_T + Z_S}$$

- Isc – symmetrical SC Current (A, rms)
- Ir – rated current (A, rms)
- Zt – transformer impedance for same voltage tap and MVA as rated current (Ir)
- Zs – system impedance in per unit on the same MVA base for rated current (Ir)

Asymmetrical Current

$$I_{SC\,(pk\ asym)} = K\, I_{SC}$$

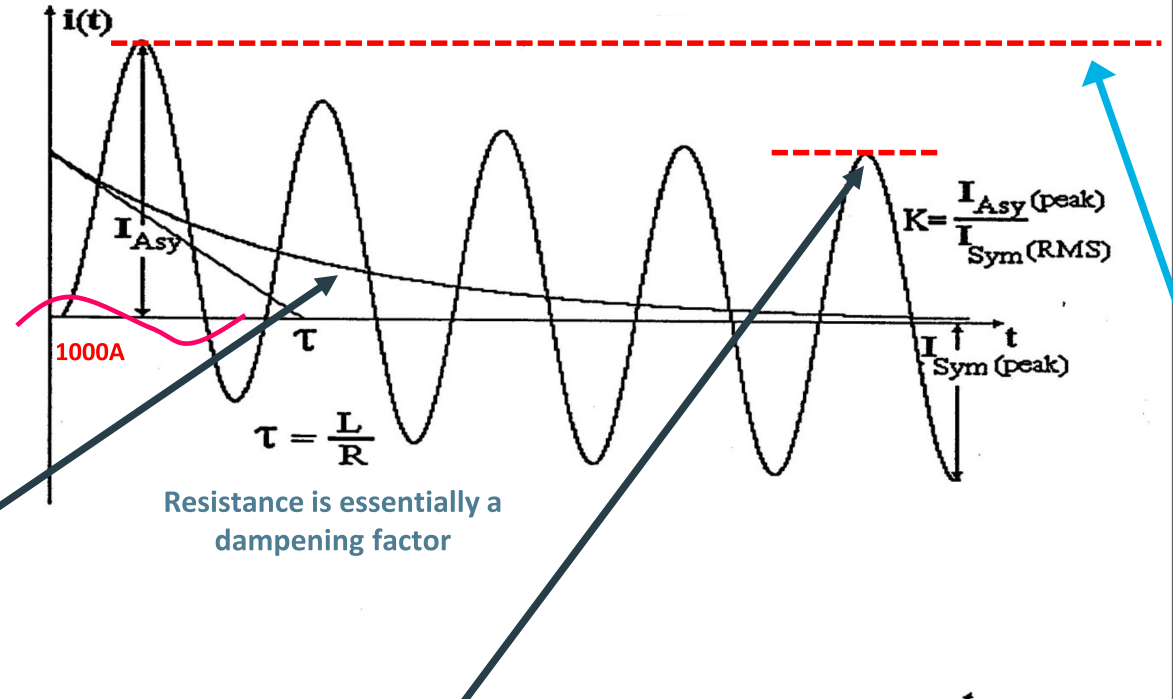
$$K = \left\{ 1 + \left[e^{-\left(\phi + \frac{\pi}{2}\right)\frac{r}{x}} \right] \sin \phi \right\} \sqrt{2}$$

ϕ is arc tan (x/r) (radians)
e is the base of natural logarithm
x/r is the ratio of effective ac reactance to resistance, both in ohms

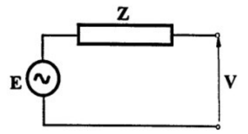
Waveform of Typical Fault Current Over Time

Symmetrical and Asymmetrical

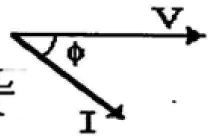
The fault current within a transformer will follow this typical exponential decay



$$i(t) = I_{Sym} Sin(\omega t - \varphi) + I_{Sym} e^{-\frac{t}{\tau}} Sin\,\varphi$$



$$Z(pu) = \frac{MVA_{Trans}}{MVA_{S/C}}$$



$$\phi = Arc\ Tan\ \frac{\omega L}{R}$$

Asymmetrical (Peak) current

$$I_{SC}\text{(peak asym)} = KI_{SC} \text{ where}$$

$$K = \left\{1 + \varepsilon^{-\left(\phi + \frac{\pi}{2}\right)\frac{r}{x}} \sin\phi\right\}\sqrt{2}, \text{ per unit}$$

$$\phi = \arctan\frac{x}{r}, \text{ radians}$$

Symmetrical (RMS) current

$$Isc = \frac{I_R}{Z_T + Z_S^*} \quad \text{OR} \quad I_{sc} = \frac{100}{\%Z} \times I_R$$

If Z was to be 8.0%, then Isc would be 12.5x normal rated current

Different Parts of the Formulas…

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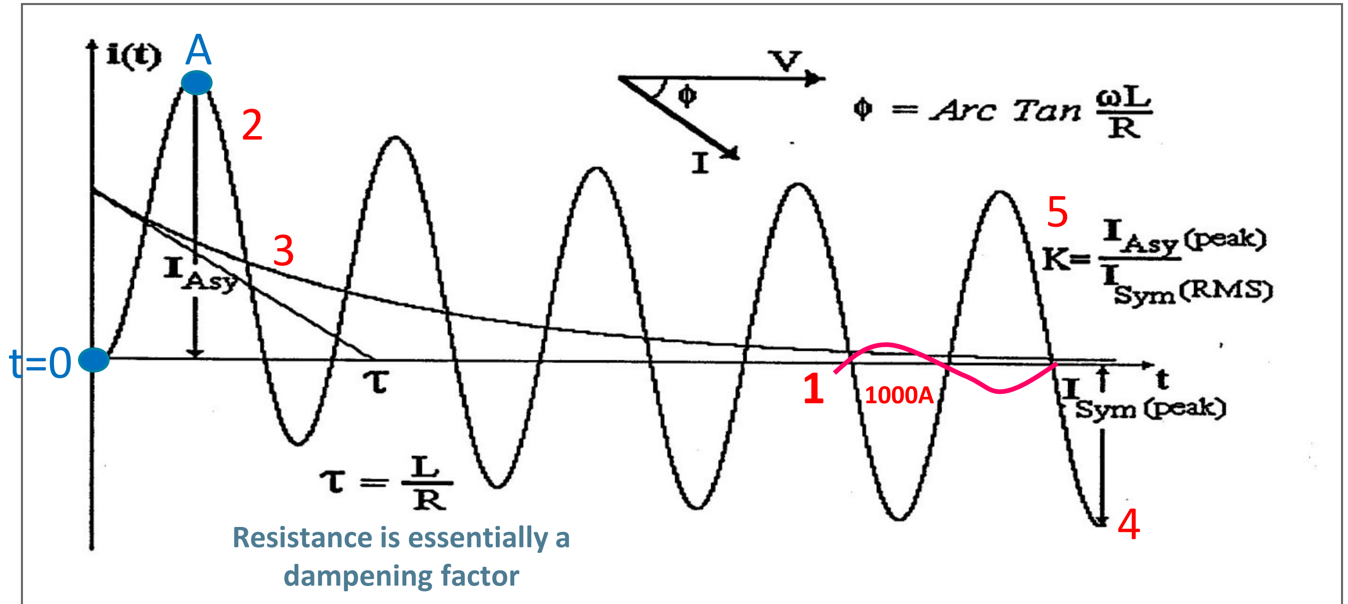

To find the current at any point in time

4 | 2, 3

$$i(t) = I_{Sym} Sin(\omega t - \varphi) + I_{Sym} e^{-\frac{t}{\tau}} Sin\ \varphi$$

4 $\quad I_{SC} = \frac{I_R \ (1)}{Z_T + Z_S}$ OR $I_{SC} = \frac{100}{\%Z} \times I_R$ 1

$$I_{SC}\text{(peak asym)} = KI_{SC} \text{ where}$$

5 $\quad K = \left\{1 + \varepsilon^{-(\phi + \frac{\pi}{2})\frac{r}{x}} \sin\phi\right\}\sqrt{2}$, per unit

$$\phi = \arctan\frac{x}{r}, \text{ radians}$$

1 – Rated current

2 – Asymmetrical current

Total fault current includes symmetrical and asymmetrical components

3 – Asymmetrical decay

Decay is an exponential function

4 – Symmetrical current

Function of rated current and impedance

5 – Asymmetry factor

Formula will calculate first asymmetrical peak – point A

Offset K factor ranges from 1.51 – 2.83, mainly dependent on x/r ratio

Convert from RMS to peak with $\sqrt{2}$

Part 4: Visualization of the Magnetic Forces

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Axial Forces on Winding Conductors (and other components)

Radial Forces on Winding Conductors

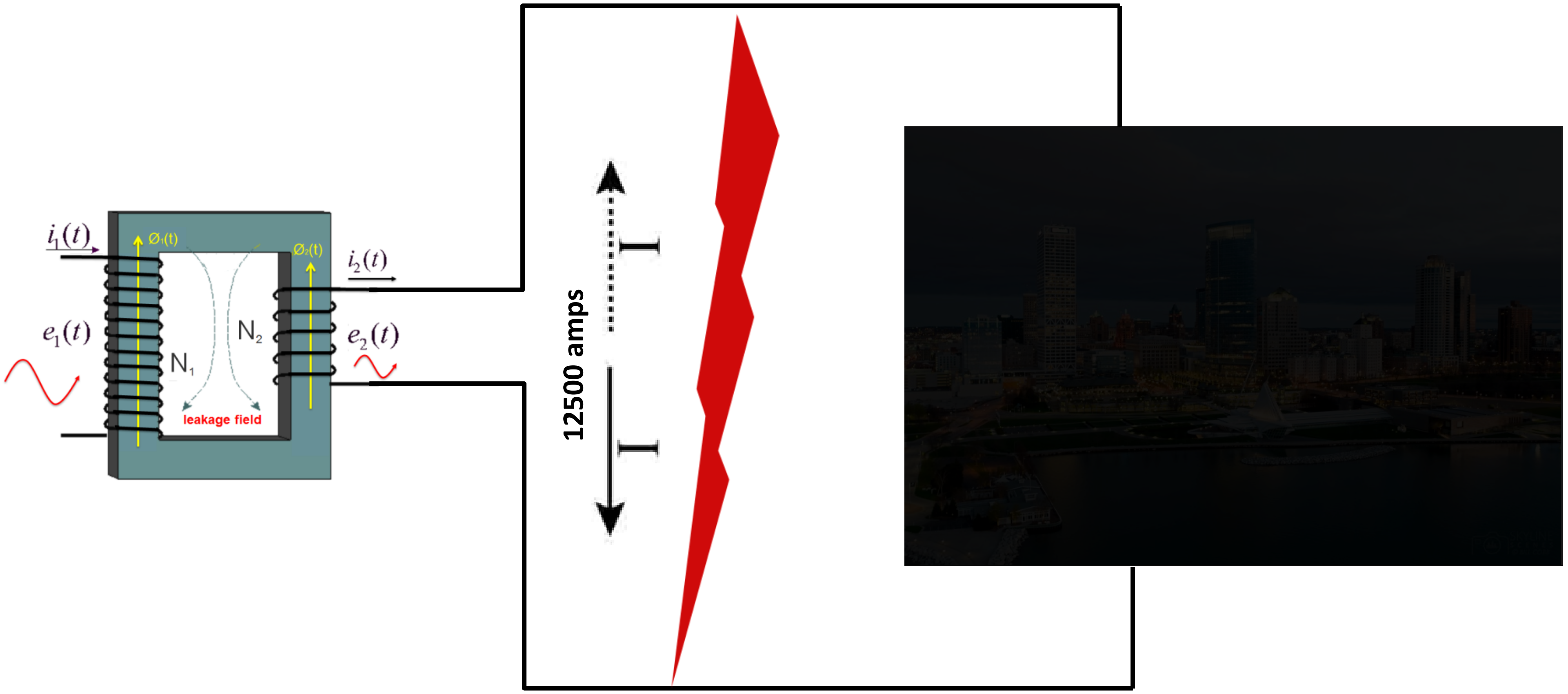
Combination of Axial/Radial Forces

Because of various directions of forces (axial, radial….forces are thus acting in 3-D

Back to our Fault Condition…

System Fault

- An un-intended “electrical connection” made between two energized components having different voltage potentials.
- Results in some (or all) of the current bypassing the intended load.
- Currents are typically very high due to low “fault impedance”



Once the Fault Occurs…

- The transformer must source the current to feed the fault

- Very high currents (much higher than rated current) begin to flow in the transformer windings

- Very high *temperatures* can be generated in the winding conductors and paper insulation resulting from the high currents that flow.

- Very high *magnetic forces* can be generated within windings, leads, supporting structures and insulation systems.

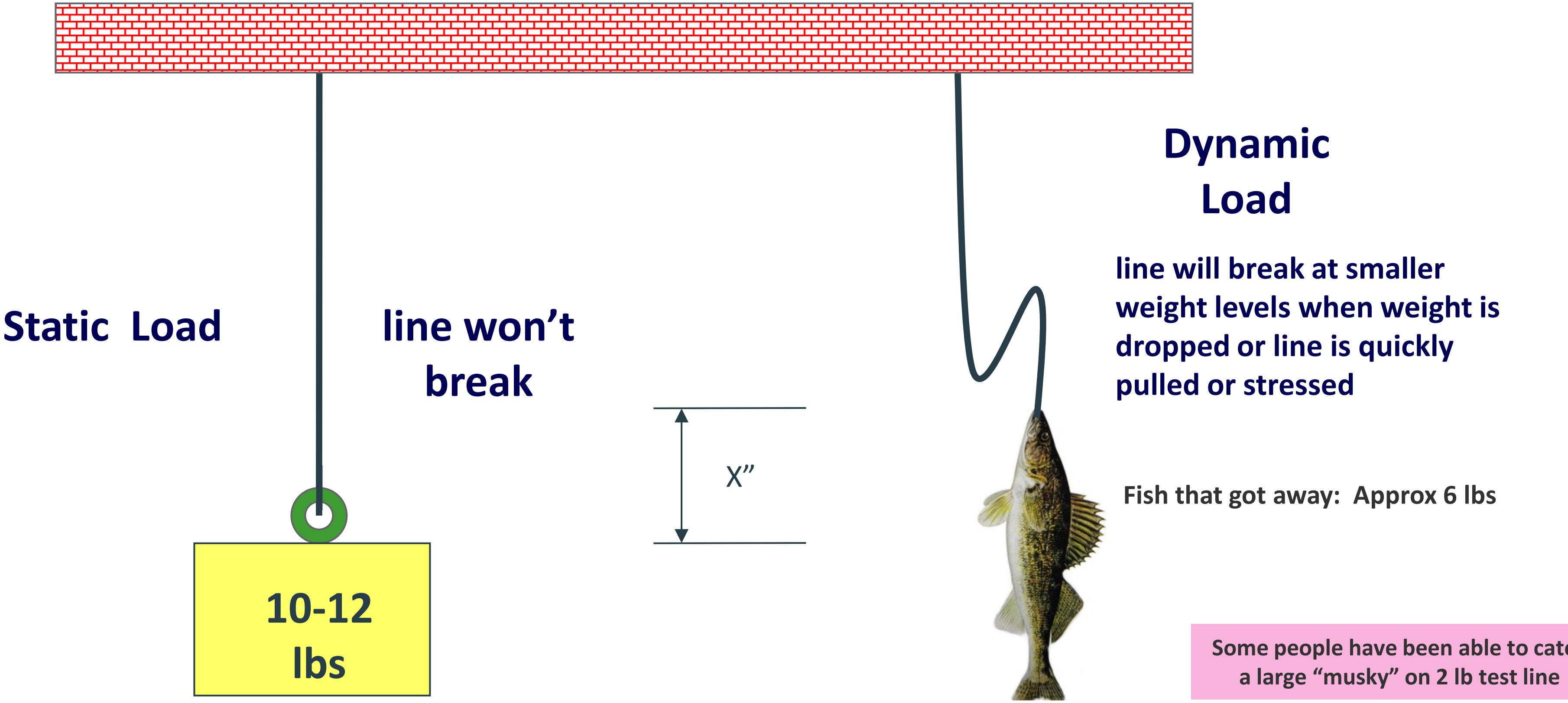
Short circuit forces are all acting in 3-D (combination of axial/radial/angular).

They can reach cumulative levels of up to 2+ million lbs, per phase, INSTANTANEOUSLY!

Physics of Materials: Static vs Dynamic Stress

We know that: All materials behave differently under static (stationary) versus dynamic (moving) load conditions

Example using a weight suspended from a 10 lb test fishing line



Some people have been able to catch a large "musky" on 2 lb test line

Visualization of Magnetic Fields and Forces

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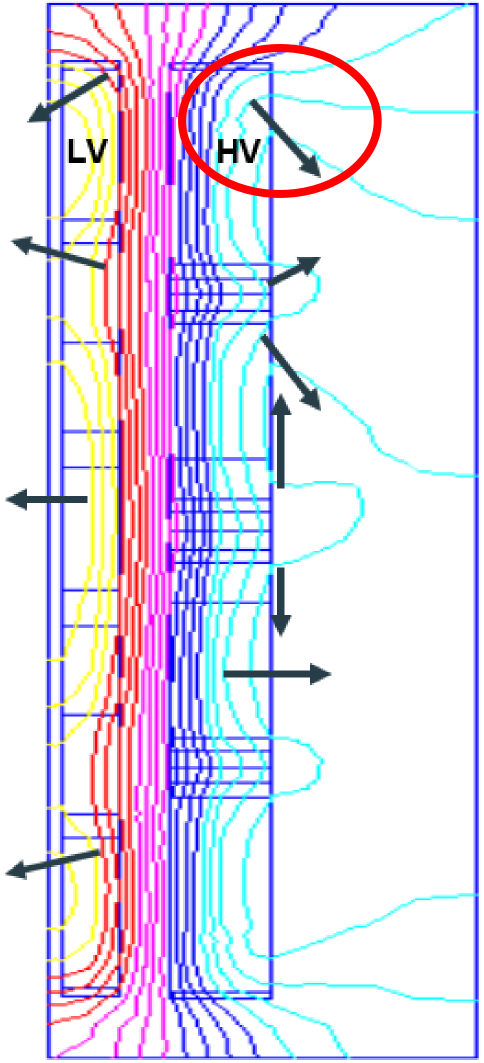
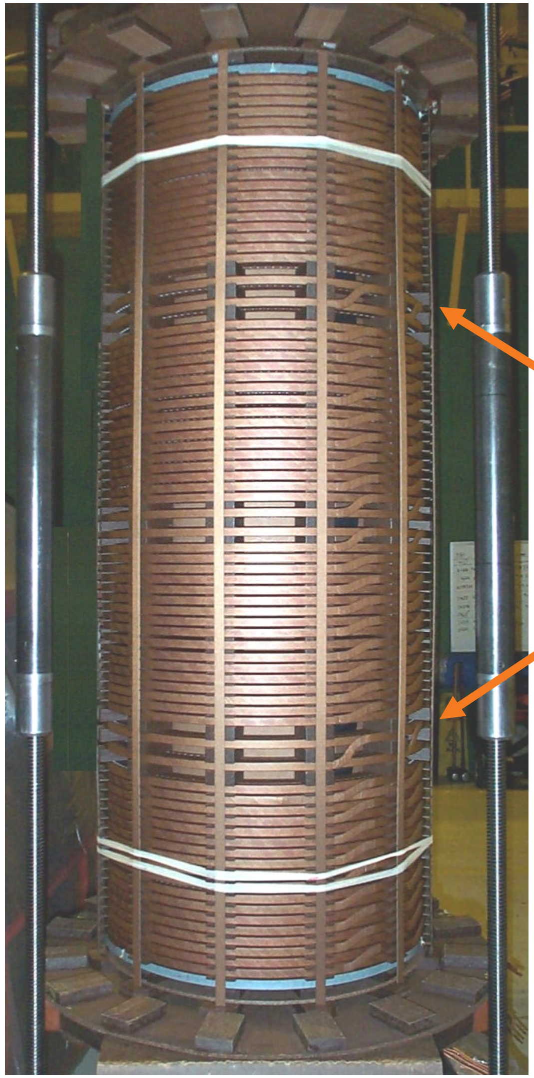
INDICATES
FORCE
DIRECTION

Mag field "leaks" out radially whenever there is an axial spreading out of turns in a coil. The larger the axial spread of turns, the more radial the field becomes

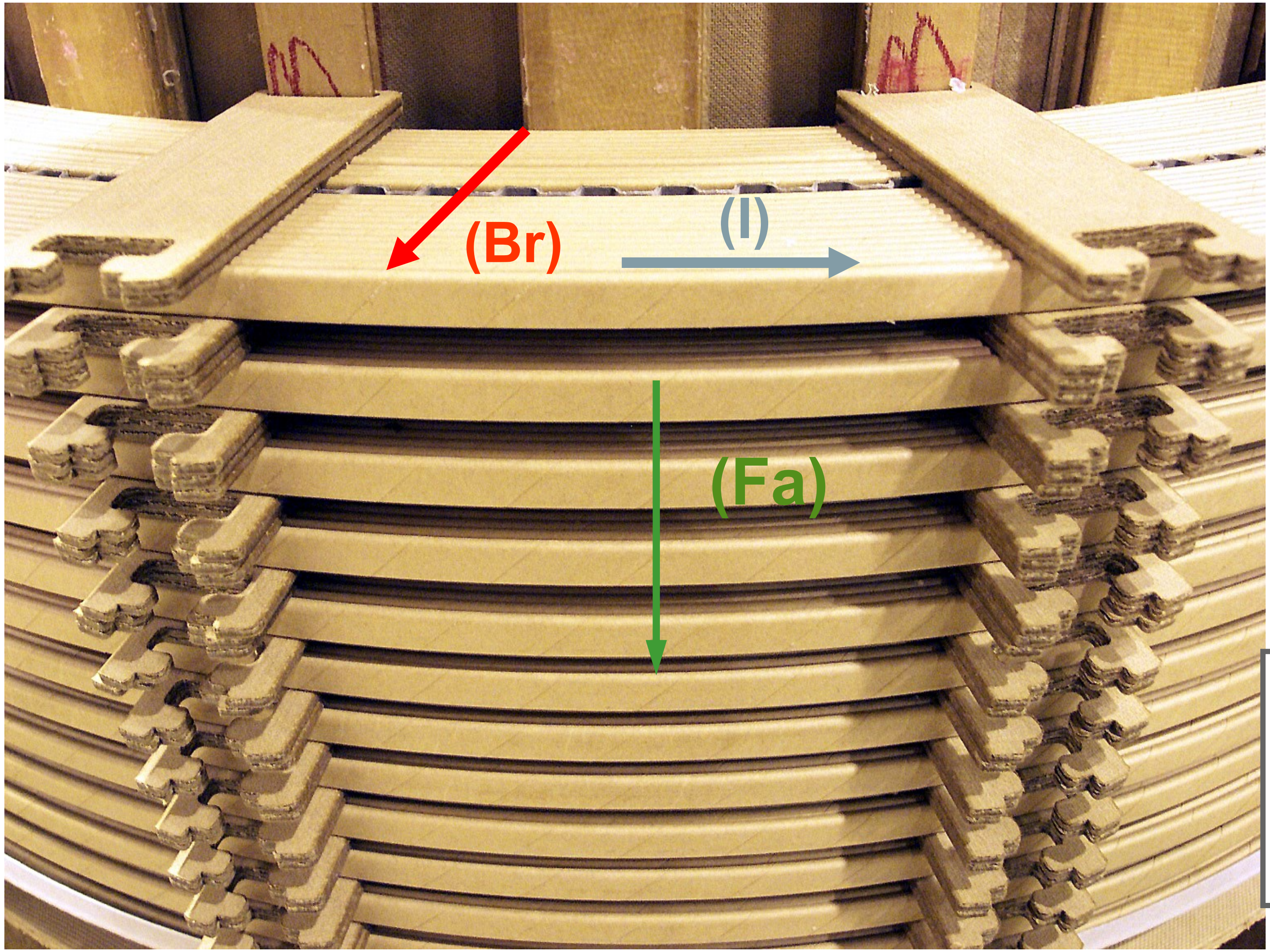


Finite Element Analysis of Leakage Flux Between Coils



Axial locations of where HV DETC taps are located

Axial Forces - (Applying Left Hand Rule)



Current (I)

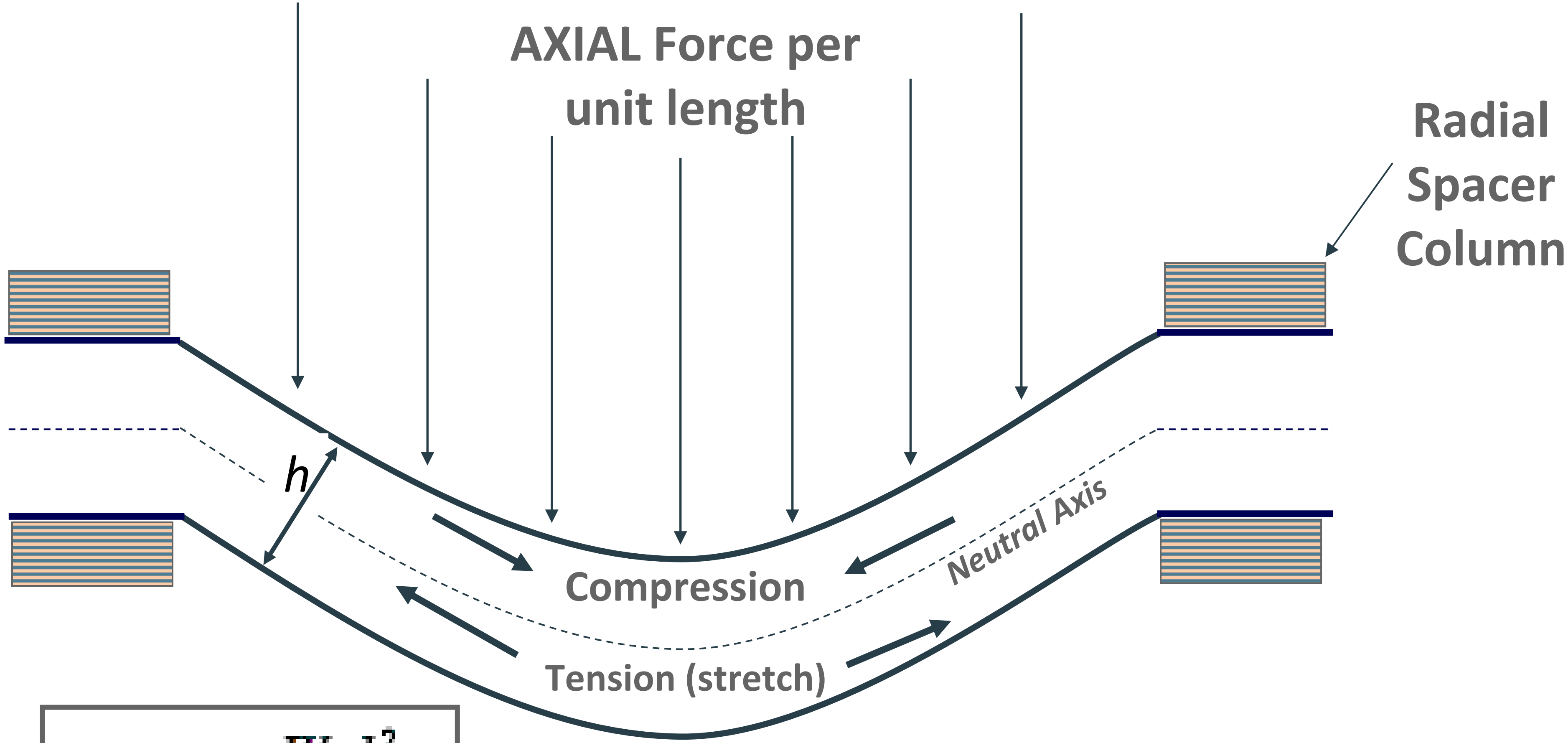
Flux (B)

Force (F)

Length of beam:

$$l = \frac{2\pi R_{OD}}{m} - W_{ks}$$

Beam Bending Under Load (elevation view)



$$\sigma_{beam} = \frac{W_a l^2}{2th^2}$$

Beam Bending Stress

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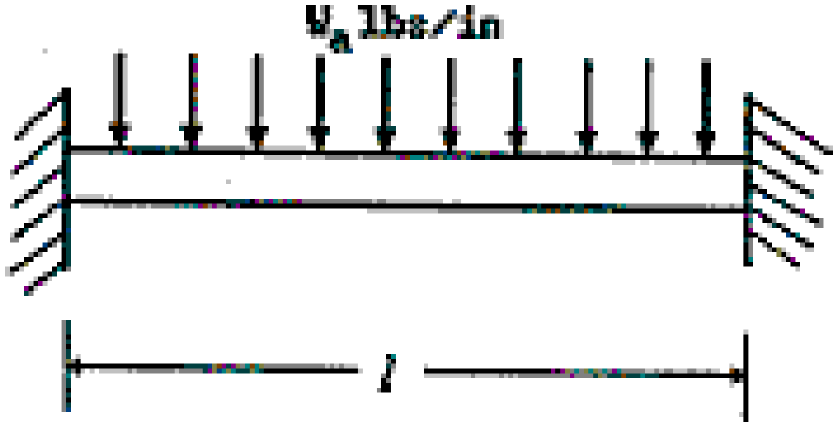
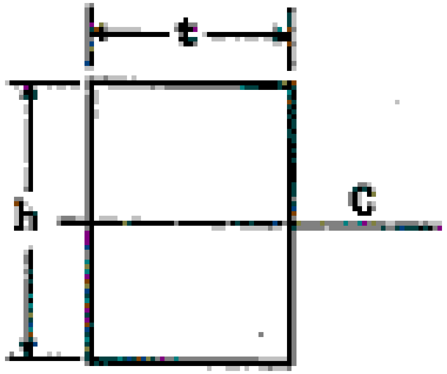




$$\sigma_{beam} = \frac{W_a l^2}{2 t h^2}$$

Length of beam:

$$l = \frac{2 \pi R_{OD}}{m} - W_{ks}$$

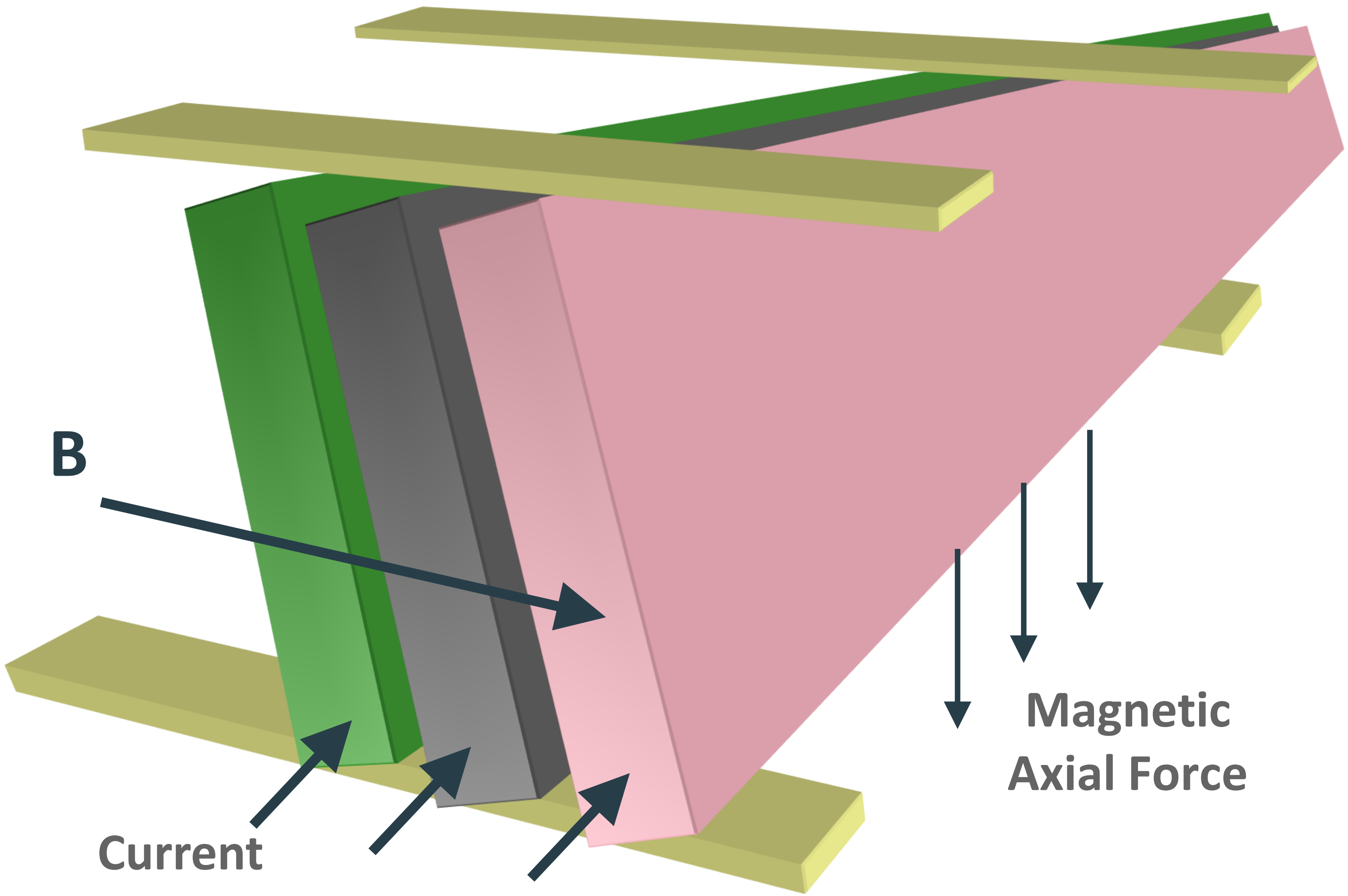
Linear Load:

$$W_a = \frac{F_{max}}{l}$$

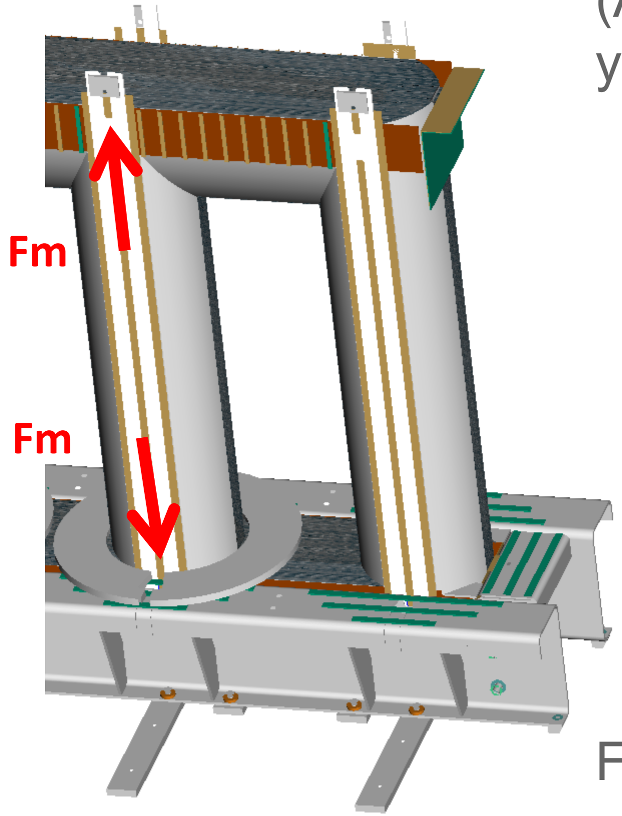
where:

R_{OD}= Winding O.D. (inches)
W_{ks}= Keyspacer Width (inches)
m= Number of Key Spacer Strings
F_{max}=Maximum Force on a Disk or Conductor (lbs)

Conductor Tipping/Tilting



Stress in Tie Bars (Verticals)



The minimum cross-sectional area of the tie bar (Atb) is determined by the force applied and the yield point of the tie bar material.

$$A_{tb} = \frac{Fm/2}{70,000}$$

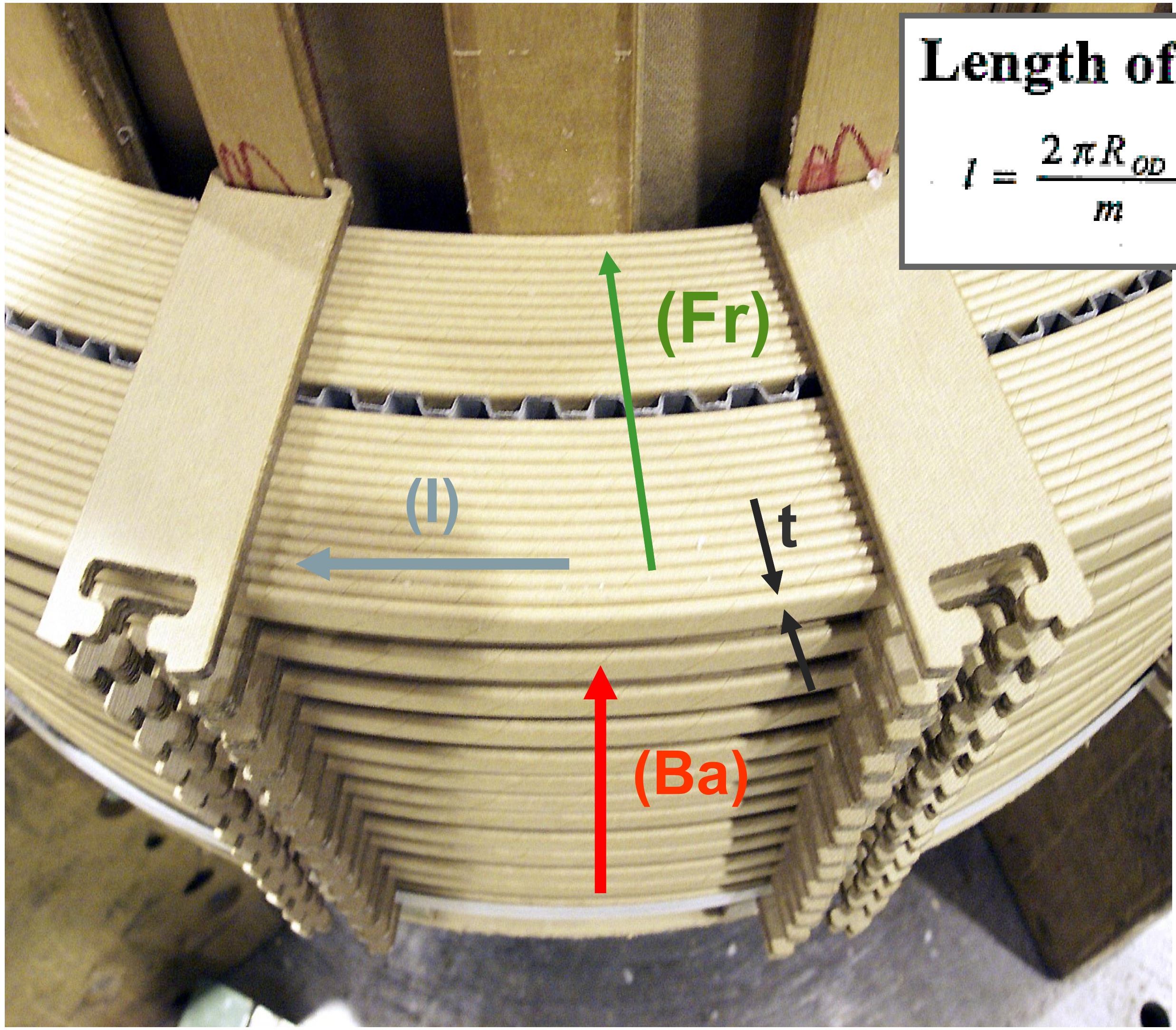
Yield Strength of Tie Bar = 100,000 PSI

70% of yield = 70,000 PSI

Fm/2 to get minimum area per tie bar (2 per phase)

Fm is the larger of:
- maximum axial short circuit force (PSI)
- maximum winding sizing per phase (PSI)

(Inward) Radial Forces – Buckling (inner coil)



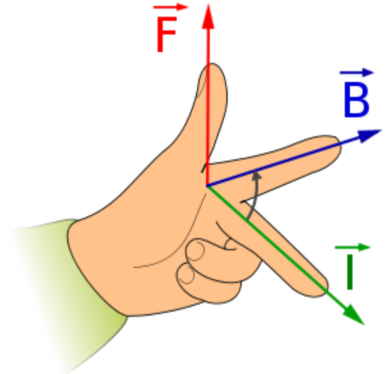
Length of beam:

$$l = \frac{2\pi R_{OD}}{m} - W_{ks}$$

Current (I)

Flux (B)

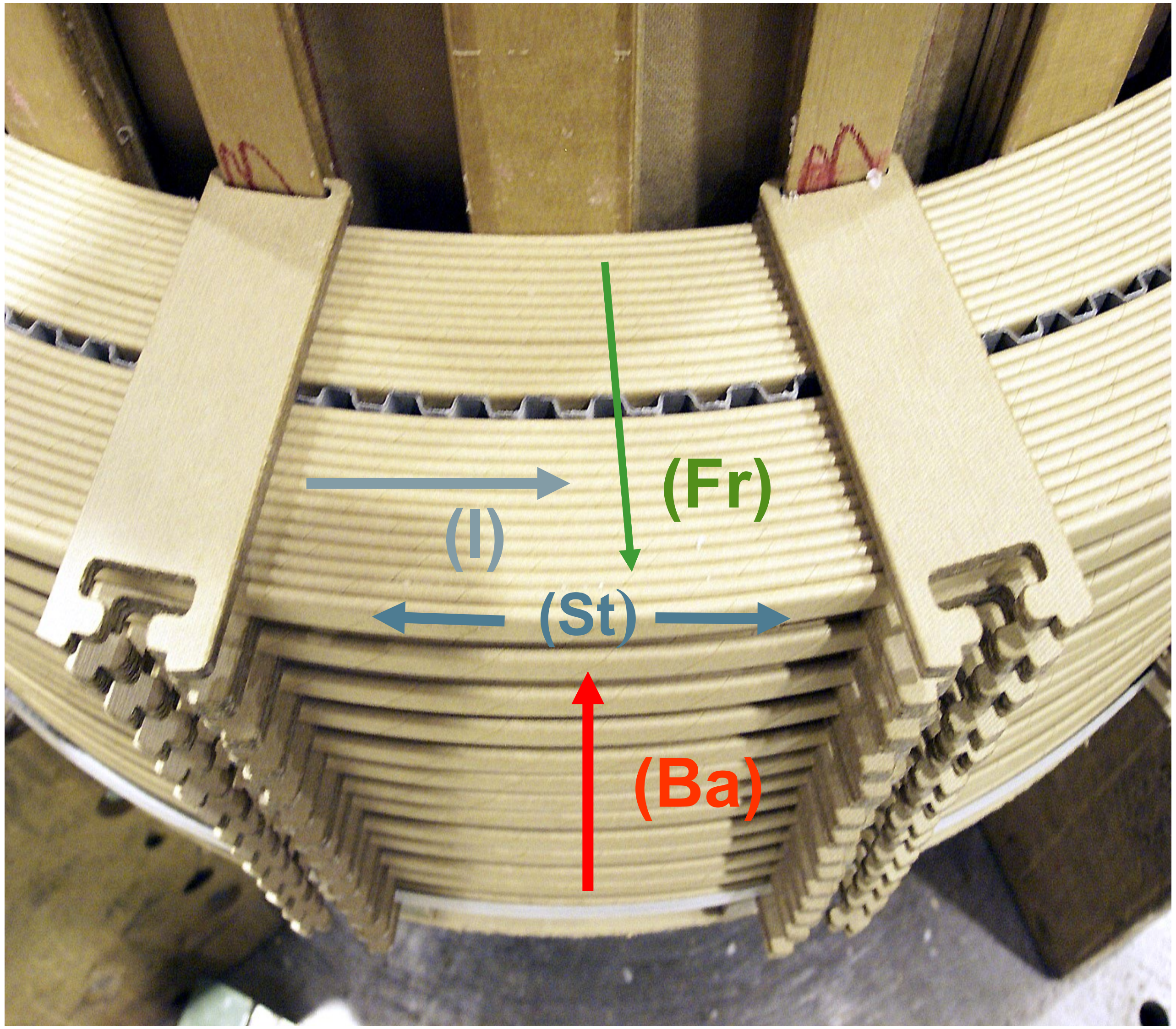
Force (F)



Left-Hand Rule

Buckling Photo - Inner Winding Forced Into Failure in a Laboratory Setting…

OUTWARD Radial Forces – Hoop Stress (outer coil)

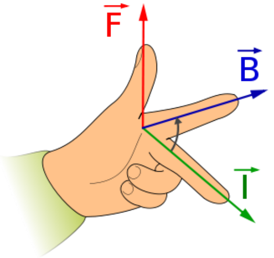


Current (I)

Flux (B)

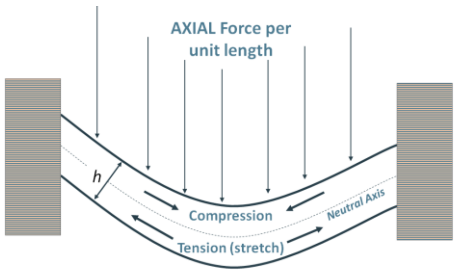
Force (F)

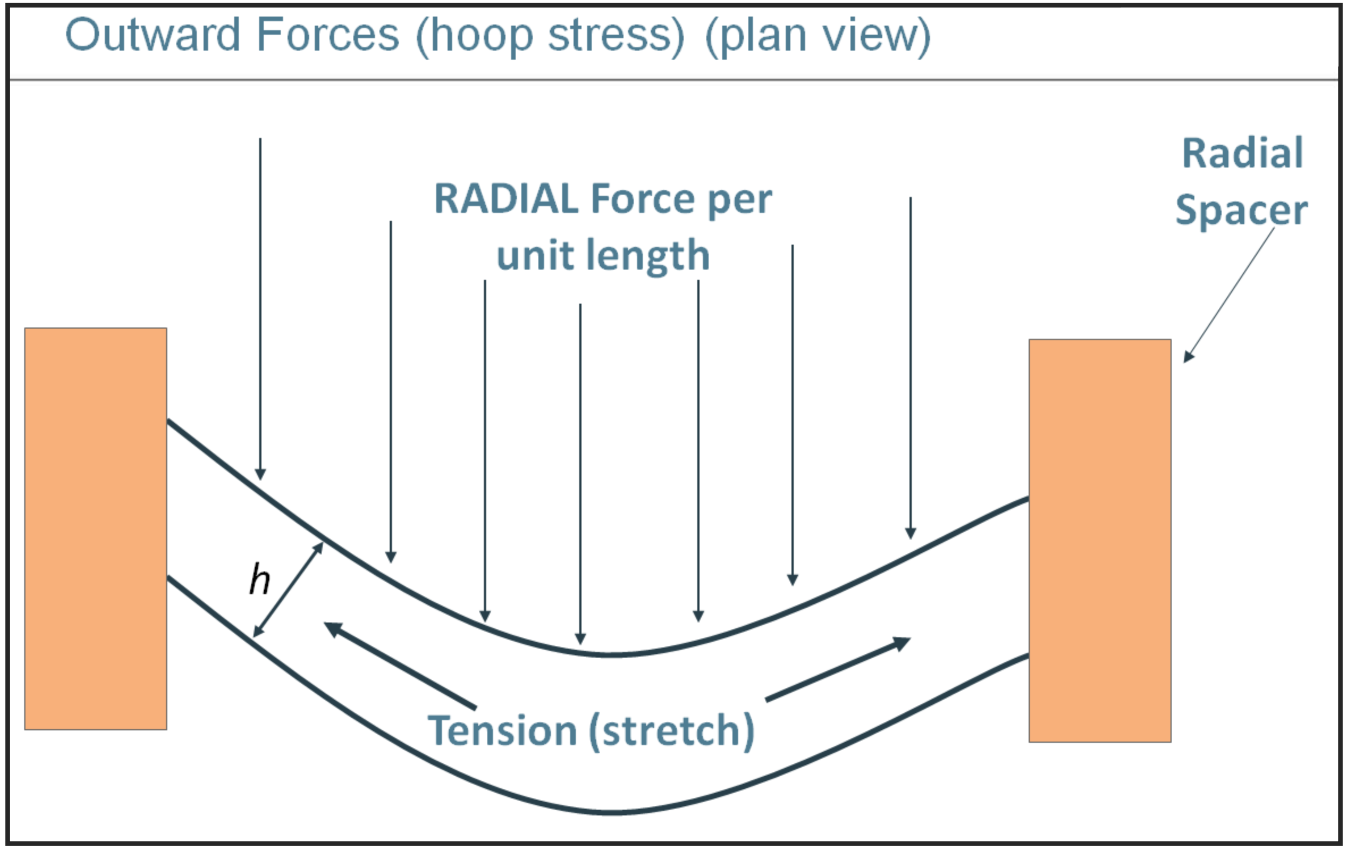
Tensile Stress (St)



Left-Hand Rule

Outward Forces (hoop stress) - Outward Radial Force exerts Tensile Stress only

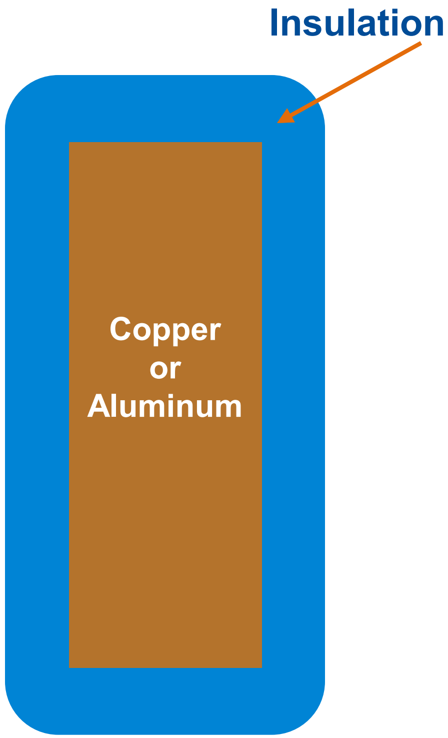




No neutral axis

Winding Temperature During a Short Circuit

- Calculated on basis that all heat is stored (heats up too quickly to radiate heat to equilibrium)
- Temperature not to exceed
  - 250°C for copper
  - 200°C for EC grade aluminum
- Method defined on
  IEEE C57.12.00-2021 section 7.4.



Insulated
Conductor

Winding Temperature During a Short Circuit

Approximate method:

$$T_f = \frac{(S_{\Delta k})^2 t}{K_m} + T_{OR} + T_a$$

T_f = final winding temperature at end of a short circuit (°C)
T_{OR} = maximum top liquid temperature rise over ambient temperature (°C)
T_a = ambient temperature (°C)
$S_{\Delta k}$ = winding loss density at symmetrical short circuit current (W/dm^2)
t = short circuit duration (s).
K_m = 156 for copper / 73 for EC grade aluminum

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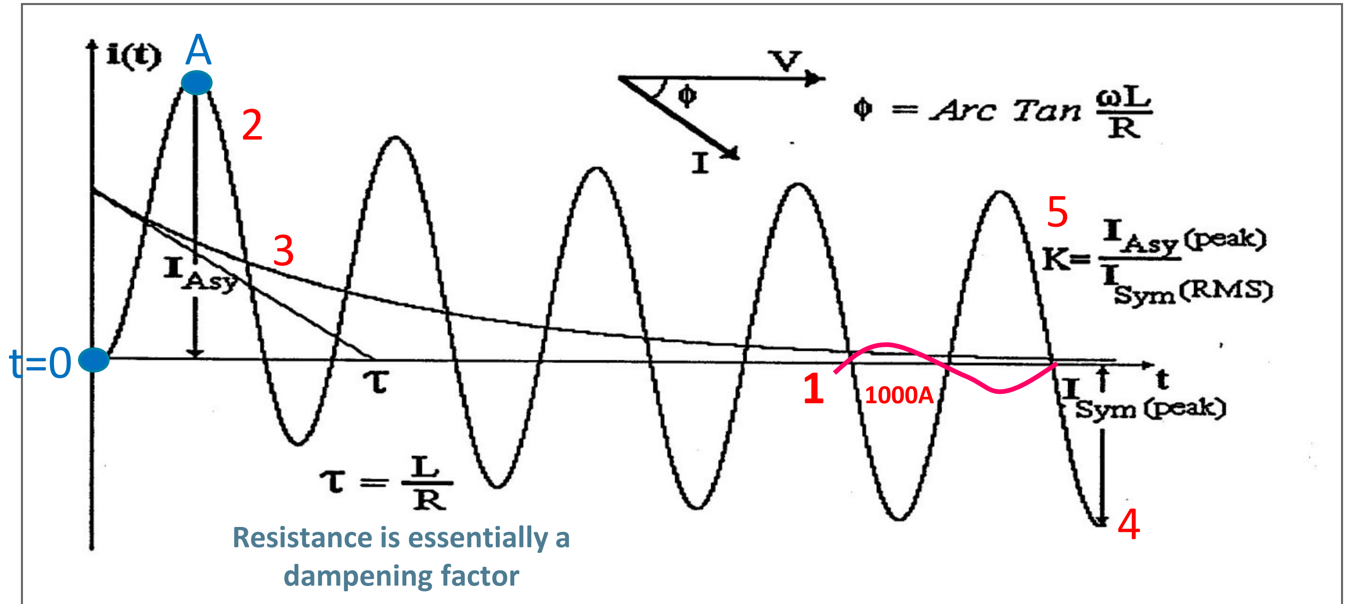
Calculate short circuit current and asymmetrical offset factor

Back to our formulas again….



To find the current at any point in time

4 | 2, 3

$$i(t) = I_{Sym} Sin(\omega t - \varphi) + I_{Sym} e^{-\frac{t}{\tau}} Sin\,\varphi$$

$$4 \quad I_{SC} = \frac{I_R \; (1)}{Z_T + Z_S} \quad \text{OR} \quad I_{SC} = \frac{100}{\%Z} \times I_R \; (1)$$

$$I_{SC}\,(\text{peak asym}) = K I_{SC} \text{ where}$$

$$5 \quad K = \left\{1 + \varepsilon^{-(\phi + \frac{\pi}{2})\frac{r}{x}} \sin\phi\right\}\sqrt{2}, \text{ per unit}$$

$$\phi = \arctan\frac{x}{r}, \text{ radians}$$

1 – Rated current

2 – Asymmetrical current

Total fault current includes symmetrical and asymmetrical components

3 – Asymmetrical decay

Decay is an exponential function

4 – Symmetrical current

Function of rated current and impedance

5 – Asymmetry factor

Formula will calculate first asymmetrical peak – point A

Offset K factor ranges from 1.51 – 2.83, mainly dependent on x/r ratio

Convert from RMS to peak with $\sqrt{2}$

Example of How to Calculate SC Current

Assume we have a transformer with a 69kV primary and the following known data:

Transformer MVA = 30 MVA base
Rated amps on LV (@ 30 MVA) = 1000 amps
Tested load loss @ 30 MVA: 72.0 kw
Tested impedance @ 30 MVA: 8.0% (= 0.08 p.u.)

To find I_{sc}(RMS symmetrical) and I_{sc}(Peak Asym), we must perform 3 steps in the following order:

1. Determine Isc (RMS symmetrical)
2. Determine offset (asymmetrical) "K" factor
3. Apply derived data from 1. and 2. to determine peak offset asymmetrical amps.

Next

Example of How to Calculate SC Current

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STEP 1: Find I_{sc}(RMS symmetrical)

Symmetrical Current without Zs

Note: Z_T and Z_s are in p.u.

$$I_{SC} = \frac{I_R}{Z_T + Z_S}$$

$$I_{SC} = \frac{1000}{0.08 + 0} = 12{,}500A$$

$$OR, using\ the\ other\ forumla\ ...$$

$$I_{SC} = \frac{100}{8\%+0\%} \text{ x } I_{rated}$$

$$I_{SC} = \frac{100}{8\%+0\%} \text{ x } 1000A = 12{,}500A$$

Symmetrical Current with Zs

$$I_{SC} = \frac{I_R}{Z_T + Z_S}$$

$$I_{SC} = \frac{1000}{0.08 + Z_s}$$

$$Z_s = \frac{MVA_T}{MVA_S} = \frac{30}{7910} = 0.38\%$$

$$I_{SC} = \frac{1000}{0.08 + 0.0038} = 11933\ A$$

Note: Zs is derived from C57.12.00-2021 Table 15 if not specified from customer.

Difference (with vs without Zs) is 567A or 4.5%

Next

Example of How to Calculate SC Current

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Step 2: Determine the "K" factor:

To find "K" factor, we need to determine %R and X/R ratio…

$$K = \left\{ 1 + \left[e^{-\left(\phi + \frac{\pi}{2}\right)\frac{r}{x}} \right] \sin \phi \right\} \sqrt{2}$$

1. Find %R

$$\%R = 100x \frac{Load\ Loss\ (kW)}{KVA_T} = \frac{100x72}{30{,}000} = 0.24\%$$

2. Find X/R

$$\frac{X}{R} = \frac{Z_T}{\%R} = \frac{8\%}{0.24\%} = 33.33$$

Plug these values into next equation

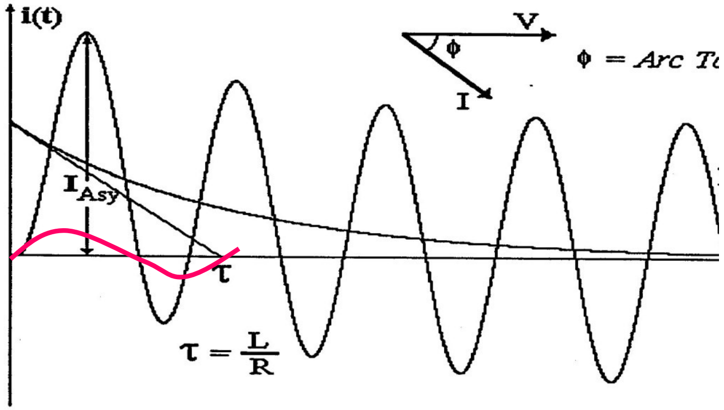
Example of How to Calculate SC Current

Step 2 (continued): Determine the “K” factor:

$$K = \left\{ 1 + \left[e^{-\left(\phi + \frac{\pi}{2}\right)\frac{r}{x}} \right] \sin \phi \right\} \sqrt{2}$$

$$K = \left\{1 + \left[e^{-\left(\tan^{-1}(33.33)+\frac{\pi}{2}\right)*\frac{1}{33.33}}\right] * \sin(\tan^{-1}(33.33))\right\} * \sqrt{2}$$

$$K = 2.702$$



C57.12.00-2010 Table 14

x/r	K
1000.00	2.824
500.00	2.820
333.00	2.815
250.00	2.811
200.00	2.806
167.00	2.802
143.00	2.798
125.00	2.793
111.00	2.789
100.00	2.785
50.00	2.743
33.30	2.702

Example of How to Calculate SC Current

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Step 3: Determine the I_{sc}(Peak Asymmetrical):

$$Since \quad Isc(peak\ asym) = K \ \ x \ \ Isc\ (RMS\ symmetrical)$$

$$then \ldots$$

$$I_{sc}(peak\ asym) = 2.702 \ \ x \ \ 12{,}500\ amps = \underline{33{,}750\ \text{amps}}$$

FYI: Since F $\propto$ I^2

The Txf forces will see $(33750 \text{ amps} / 1000 \text{ amps})^2 = (33.75)^2 = 1140$ x normal forces

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Questions ???

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