# Regional Technical Seminar

# Short Circuit Design Considerations

Transformer Regional Technical Seminar

Minneapolis , MN

August 15, 2024

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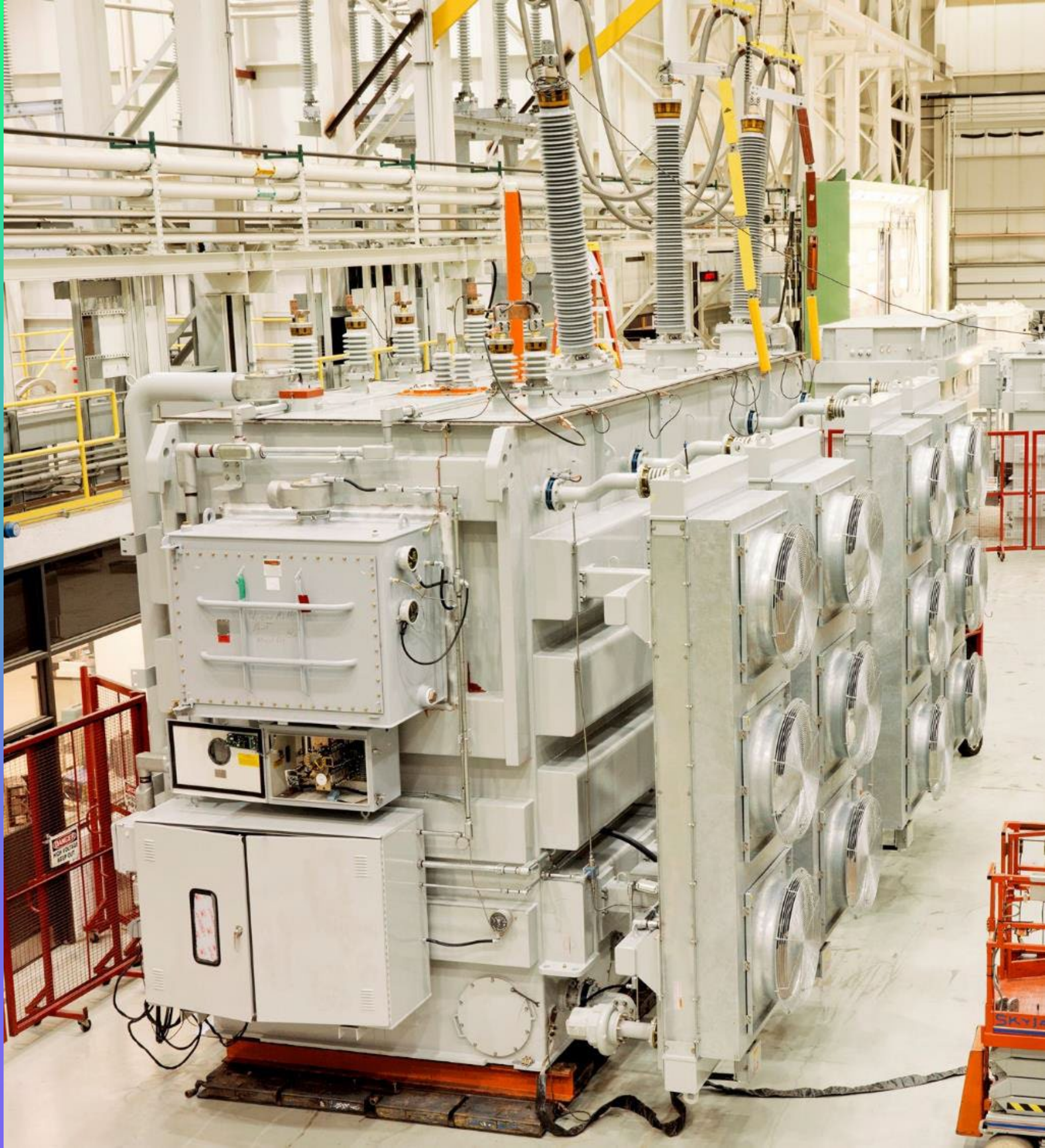
# Michael Liesch

## Senior Electrical Design Engineer

*Mike started with Prolec GE Waukesha in 2016, bringing with him 3 years of experience in inspecting and testing transformers. He holds a Bachelors of Science degree in Electrical Engineering from the Milwaukee School of Engineering.*



# Agenda

- 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

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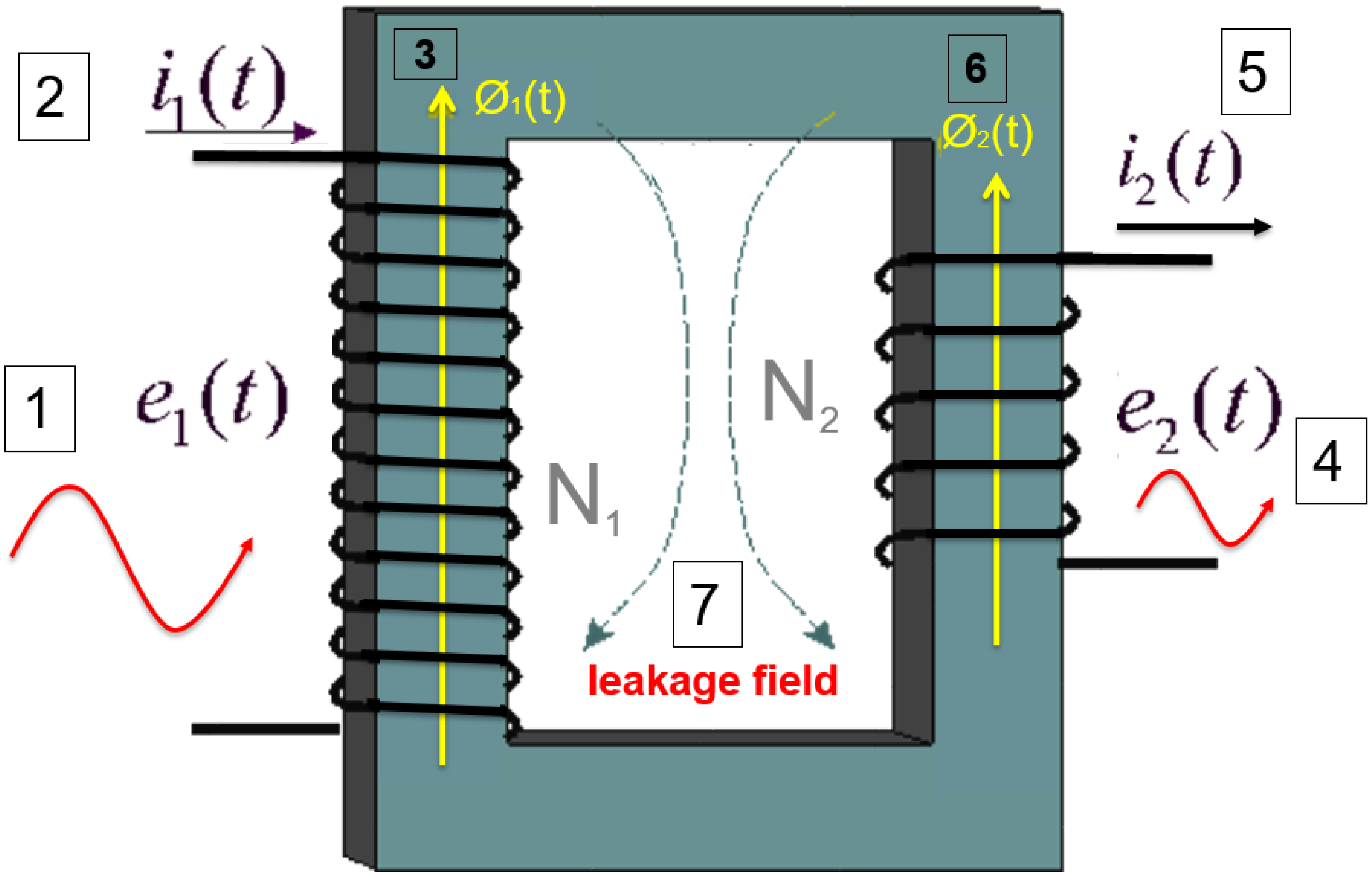
# Part 1 – Transformer Basics:

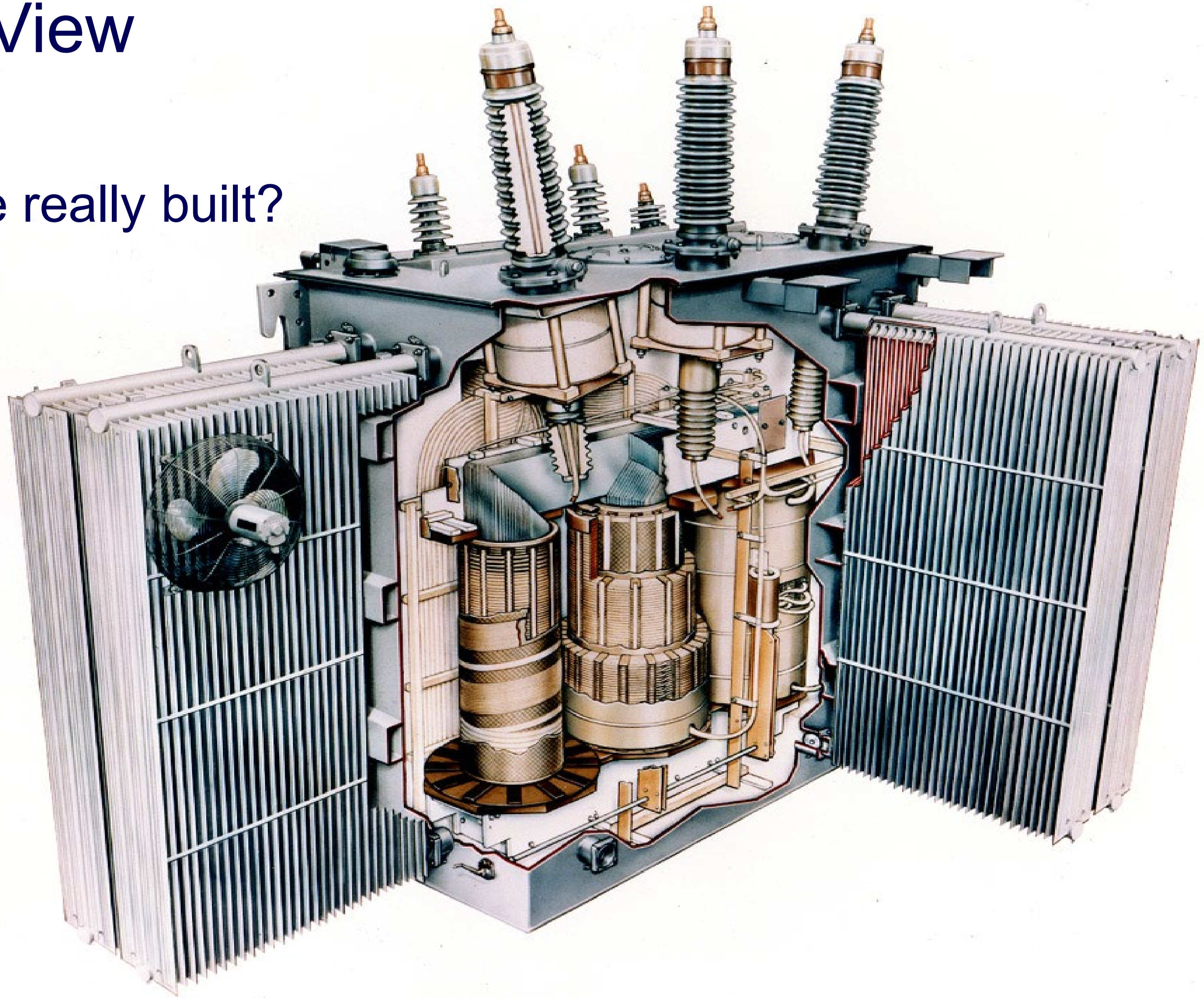
- How they work
- How they are actually built

# Textbook Transformer (step by step)

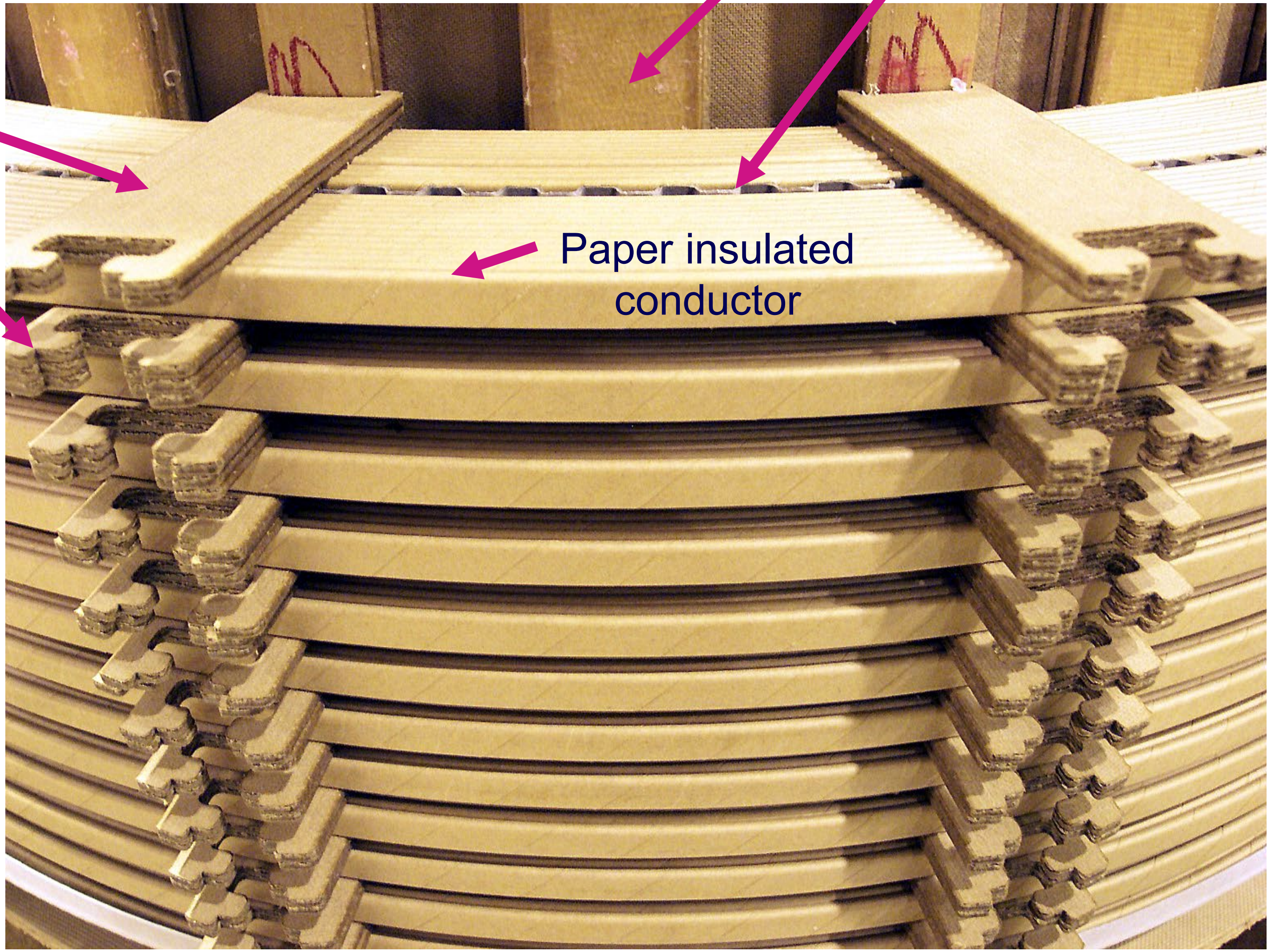


# Cutaway View

How they are really built?



# Close up of Coil Construction



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# Part 2 – Transformer Basics:

- Fundamentals of Magnetics and Forces
- Magnetic Fields Around Conductors
- Forces That Result

# Current & Magnetic Field Relationships

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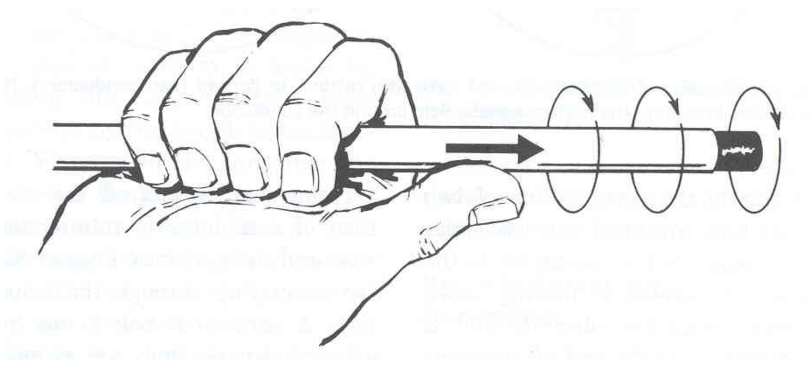
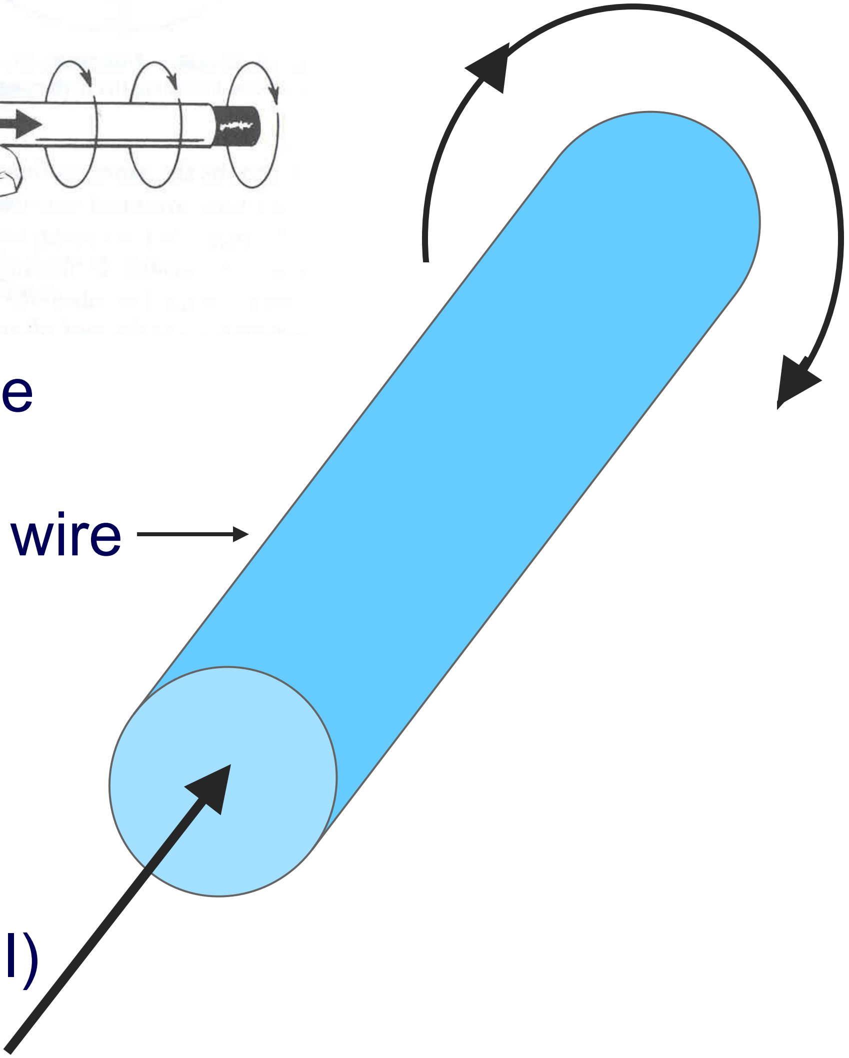


Right hand rule

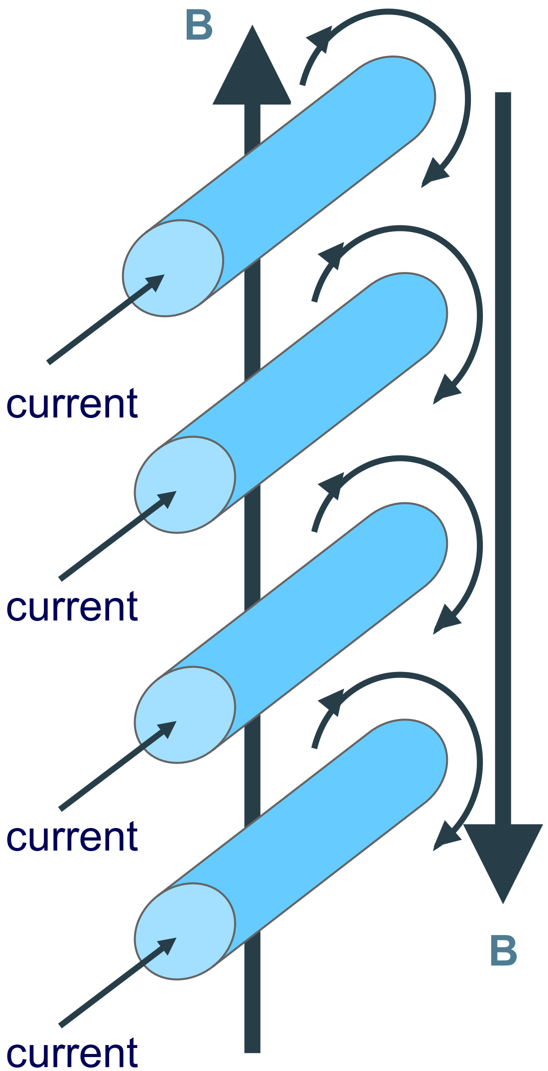
Consider a section of wire

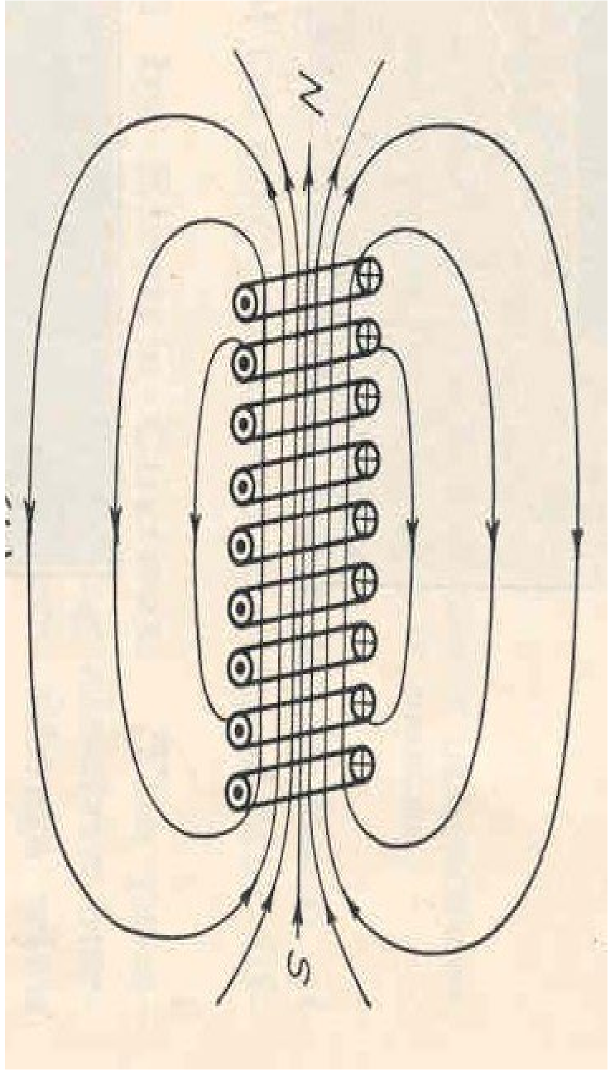


resulting magnetic field direction (CW)

Current Flow (I)

# Effect of Many Turns

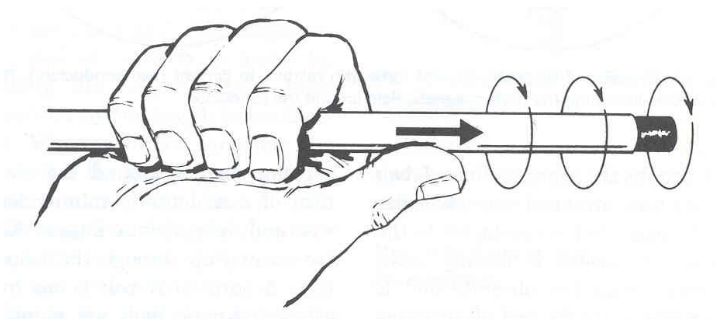


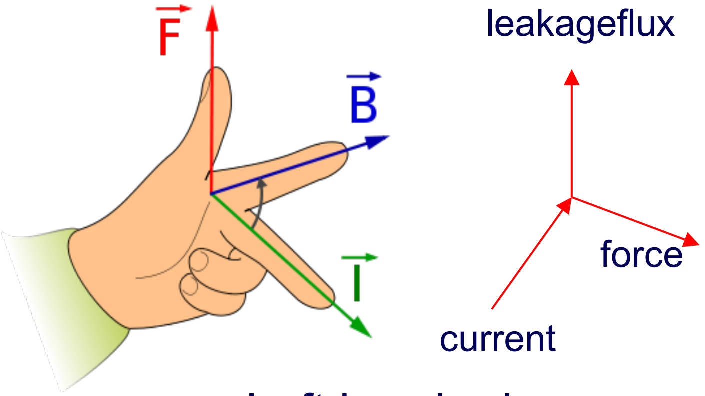

- Fields at inner/outer edges add together.
- One uniform magnetic path results
- Magnetic field (B) intensifies with # turns (N) or the current (I).

$$B \propto NI$$

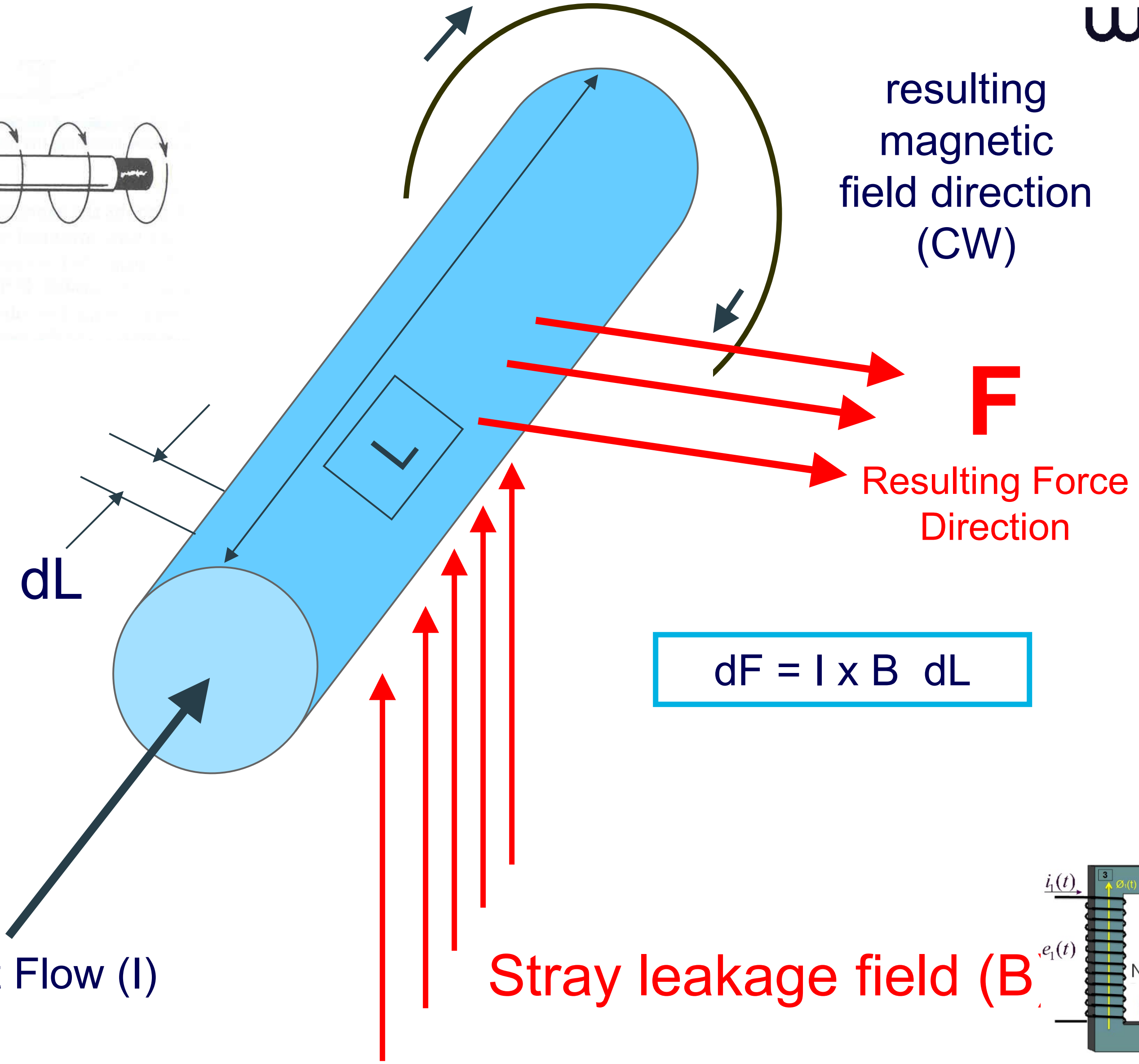
# Leakage Field / Current / Force Relationships



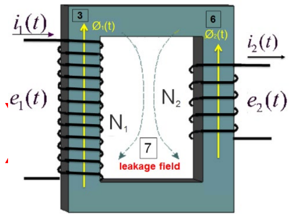
Right hand rule



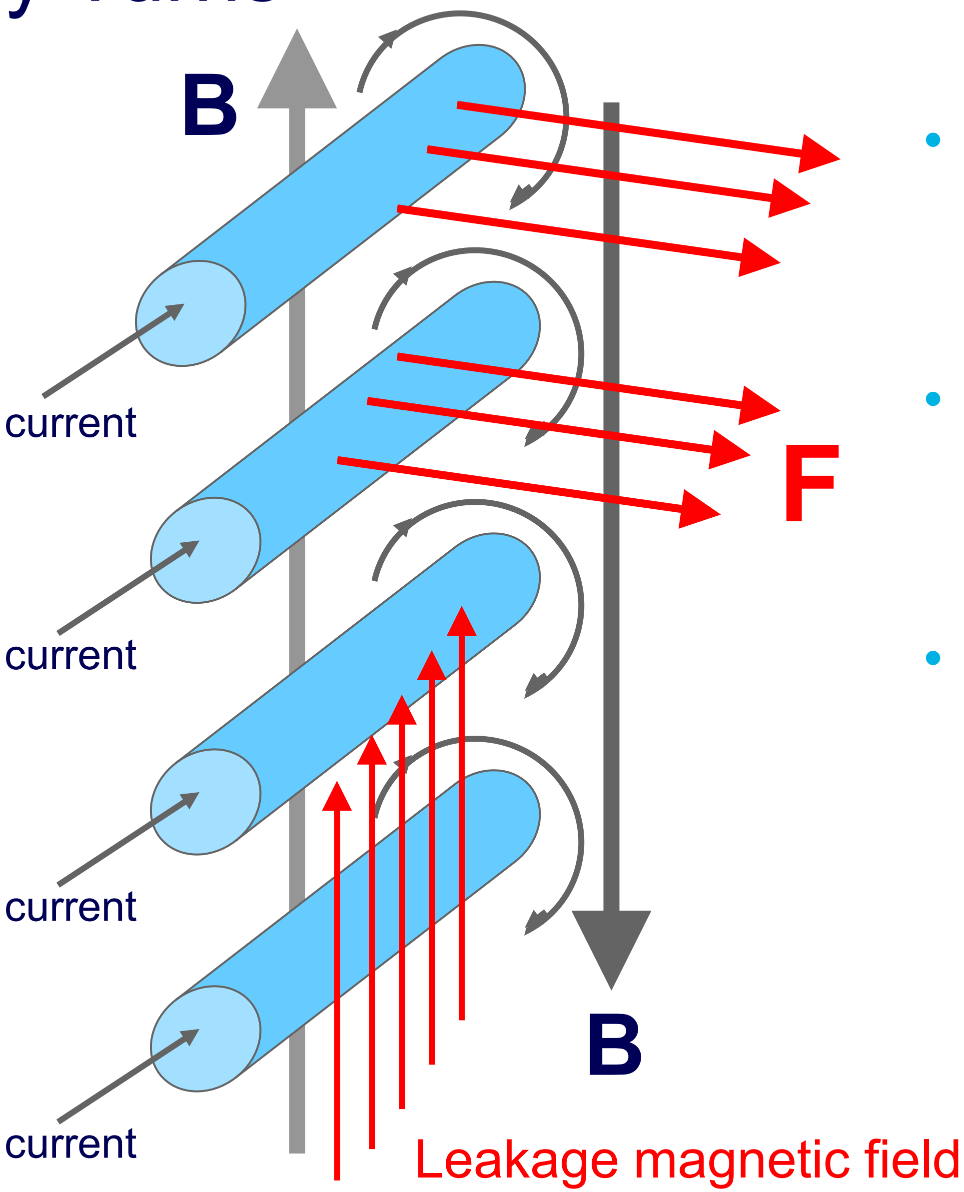

Left hand rule




dF = I x 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)

$$B \propto NI$$

$$dF = N \times I\,B\,dL$$

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

# Magnetic “Leakage” Field Across the Coils & Resulting Forces

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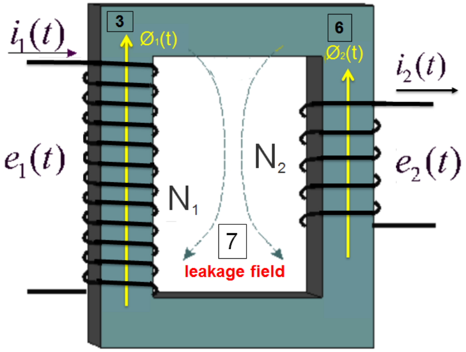
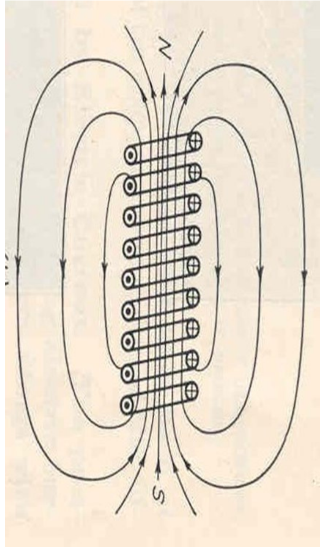
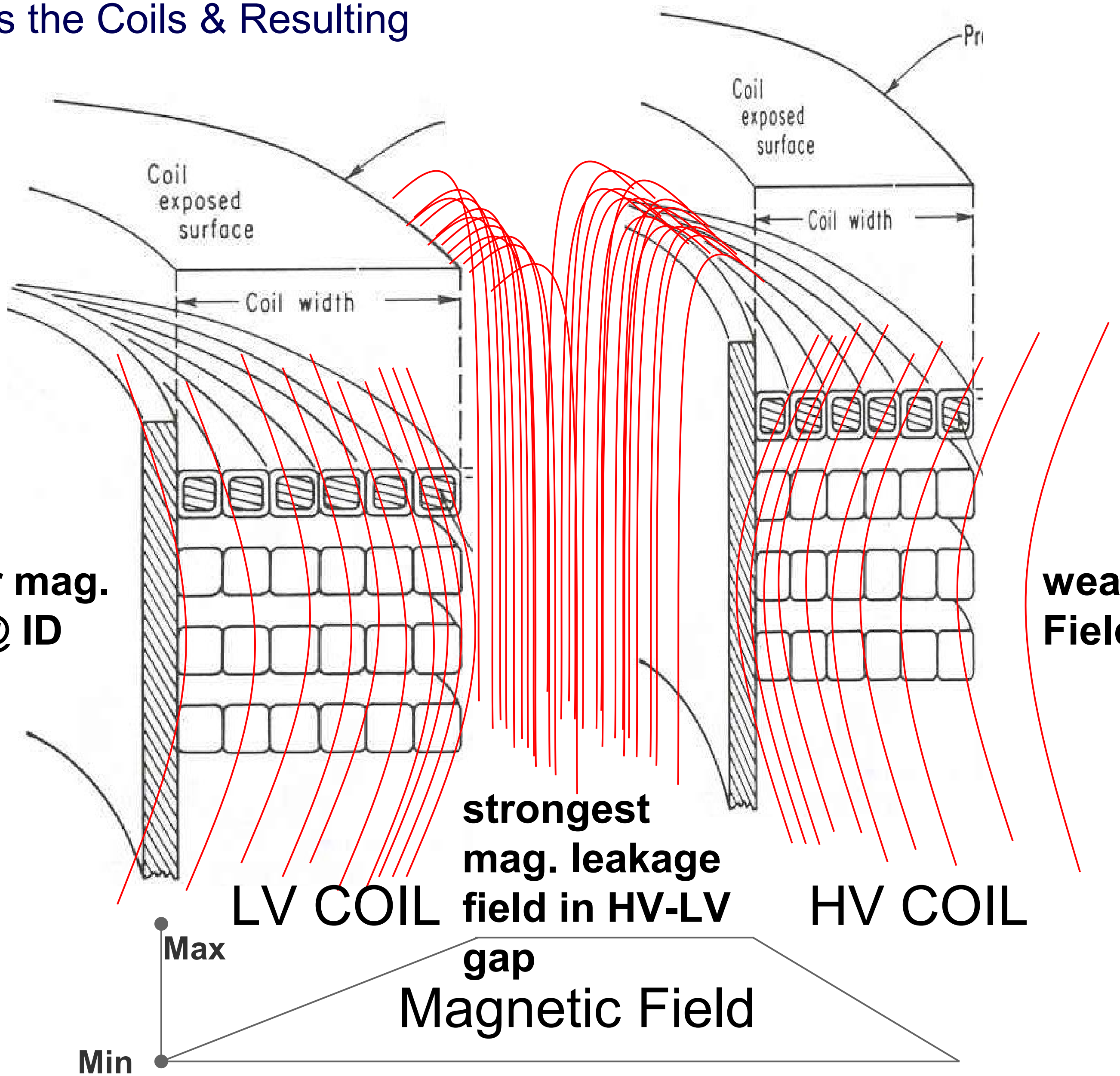


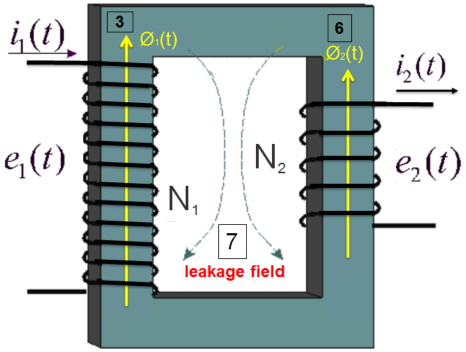



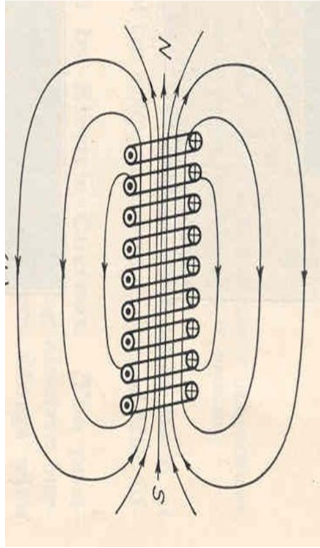

**weaker mag. Field @ ID**

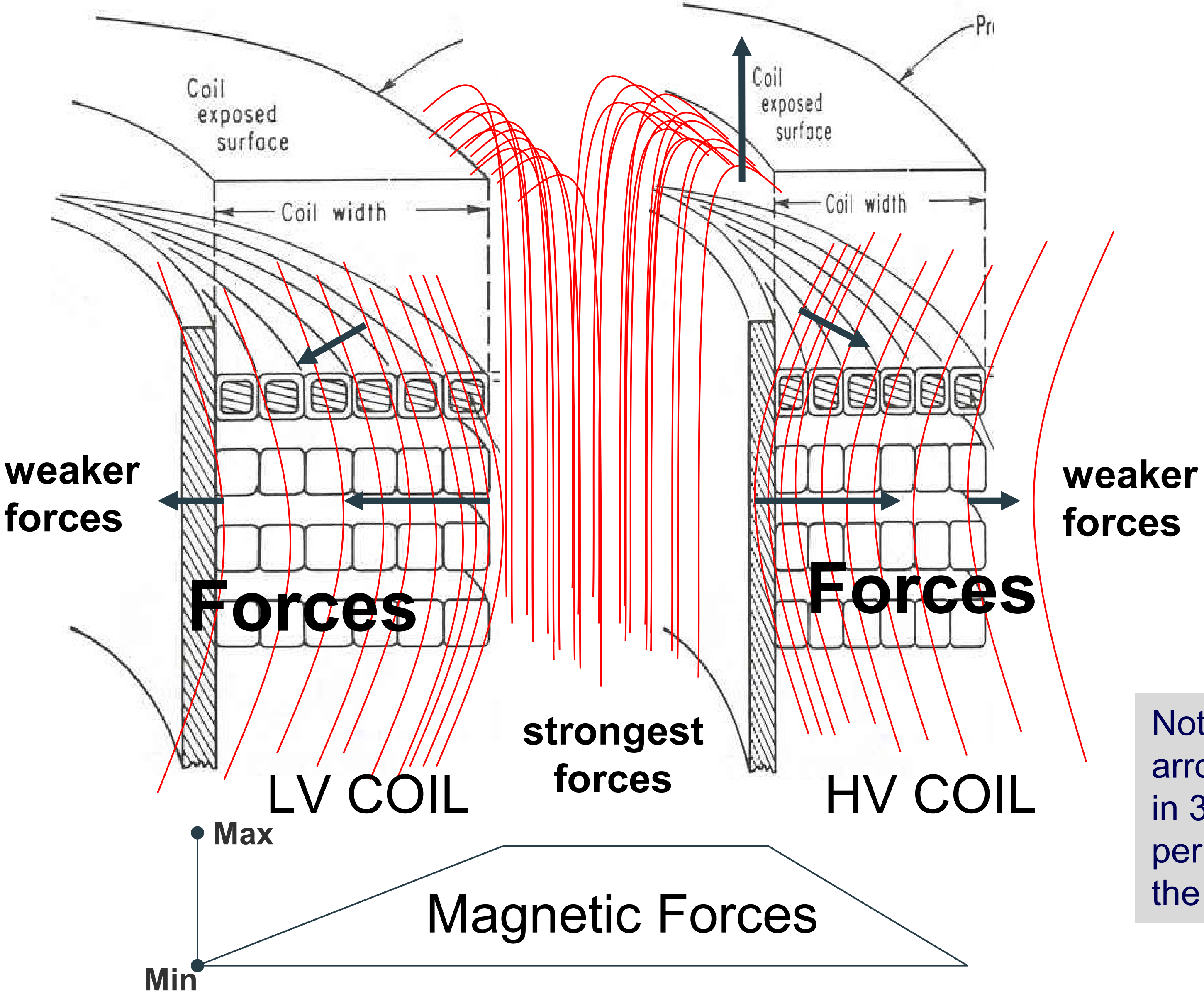



**weaker mag. Field @OD**

# Magnetic Forces Across the Coils



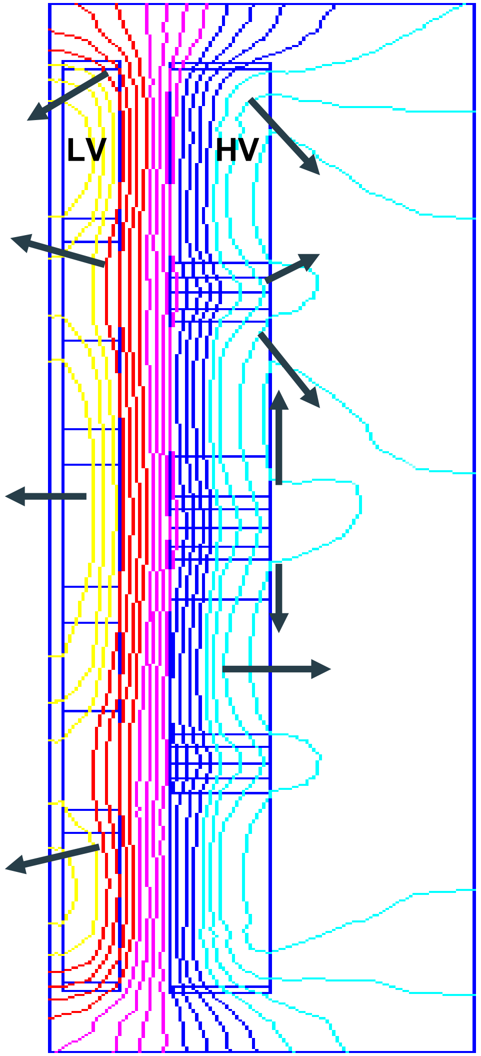



Note: The force arrows are acting in 3-D and perpendicular to the mag fields

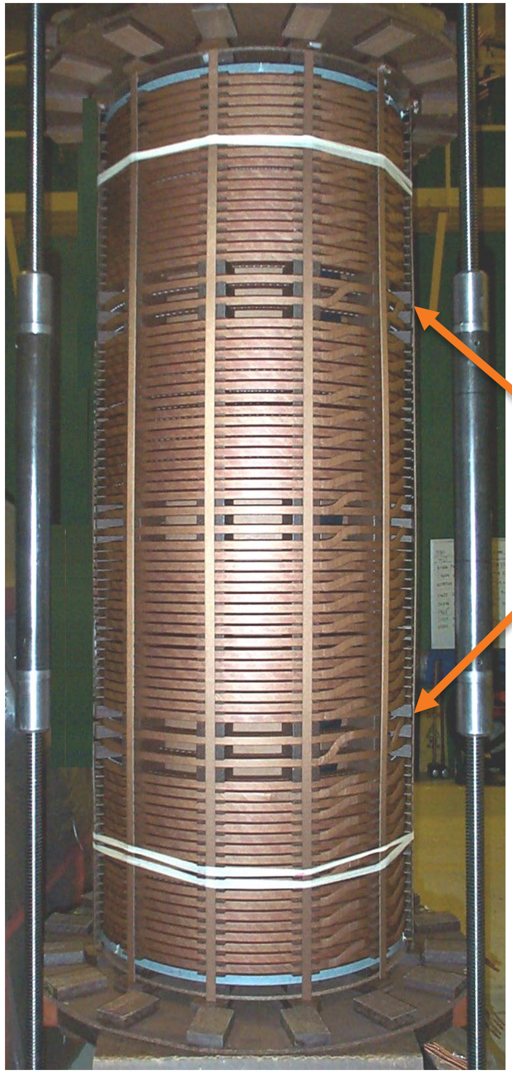
# Pictorial of actual FEA field plots

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 Field Between Coils**



**Axial locations of where HV DETC taps are located**

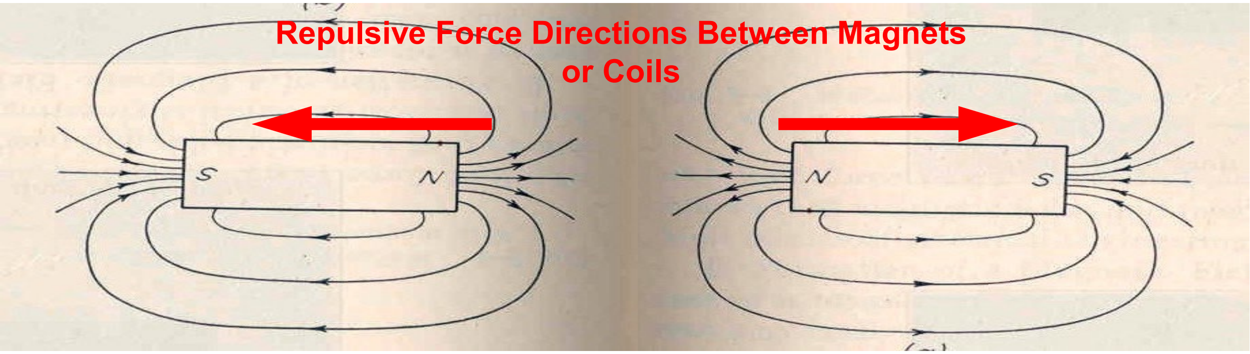
Note: The force arrows are acting in 3-D and perpendicular to the mag fields

# 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

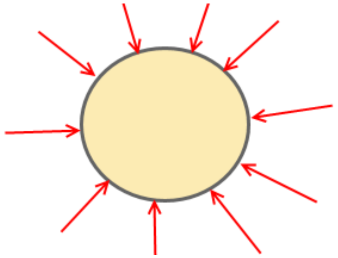
# Magnetic Forces

- 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.



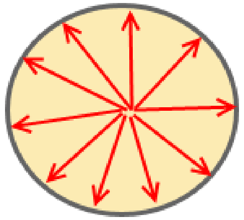

Summative force between these coils could be millions of pounds

- The inner coil experiences net inward radial “crushing” compressive forces



LV coil

- The outer coil experiences net outward radial expanding type forces



HV coil

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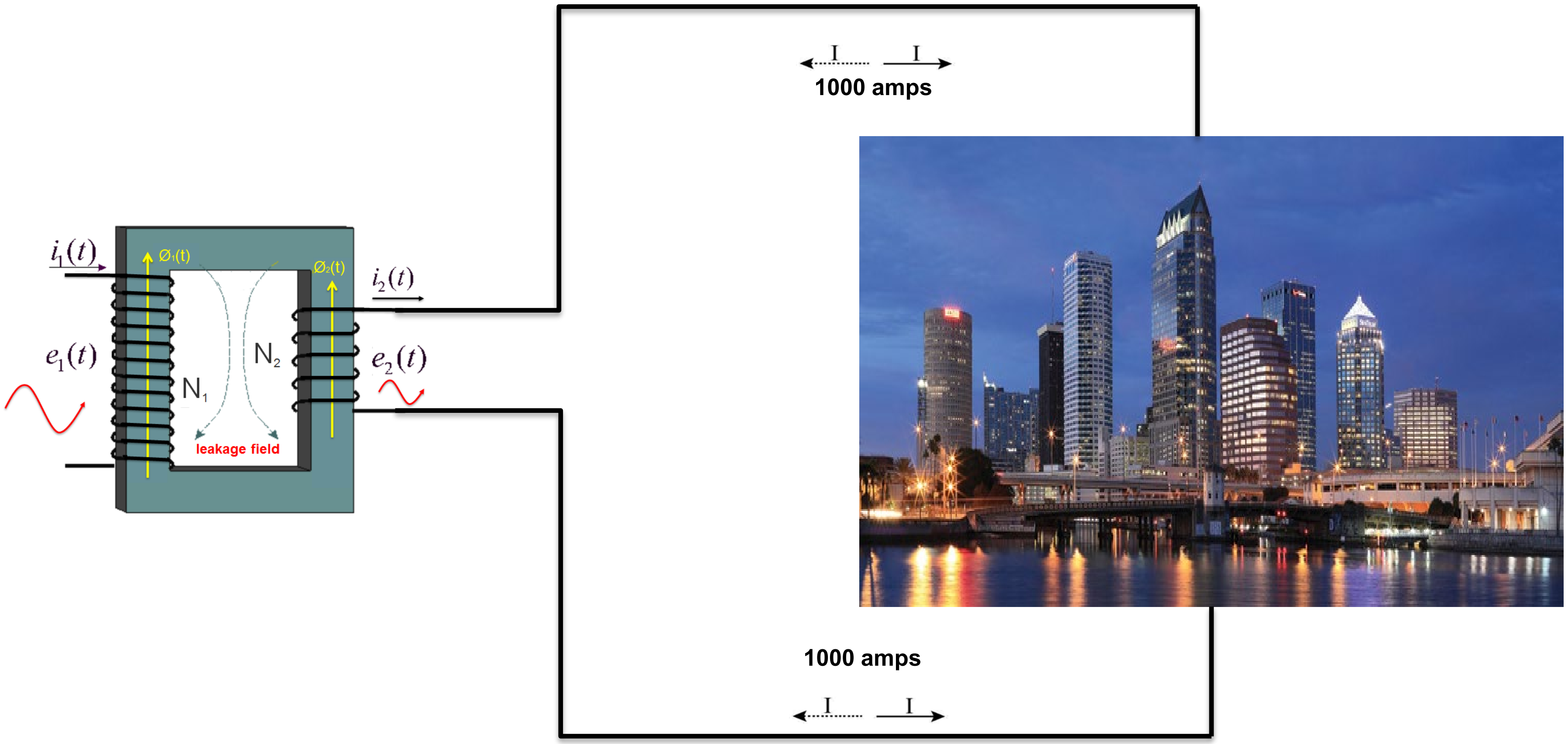
# Part 3 – Short Circuits (Faults):

- What are they?
- How do they happen?
- What do they do to my transformer?

# Normal Transformer Operation

## Normal Circuit

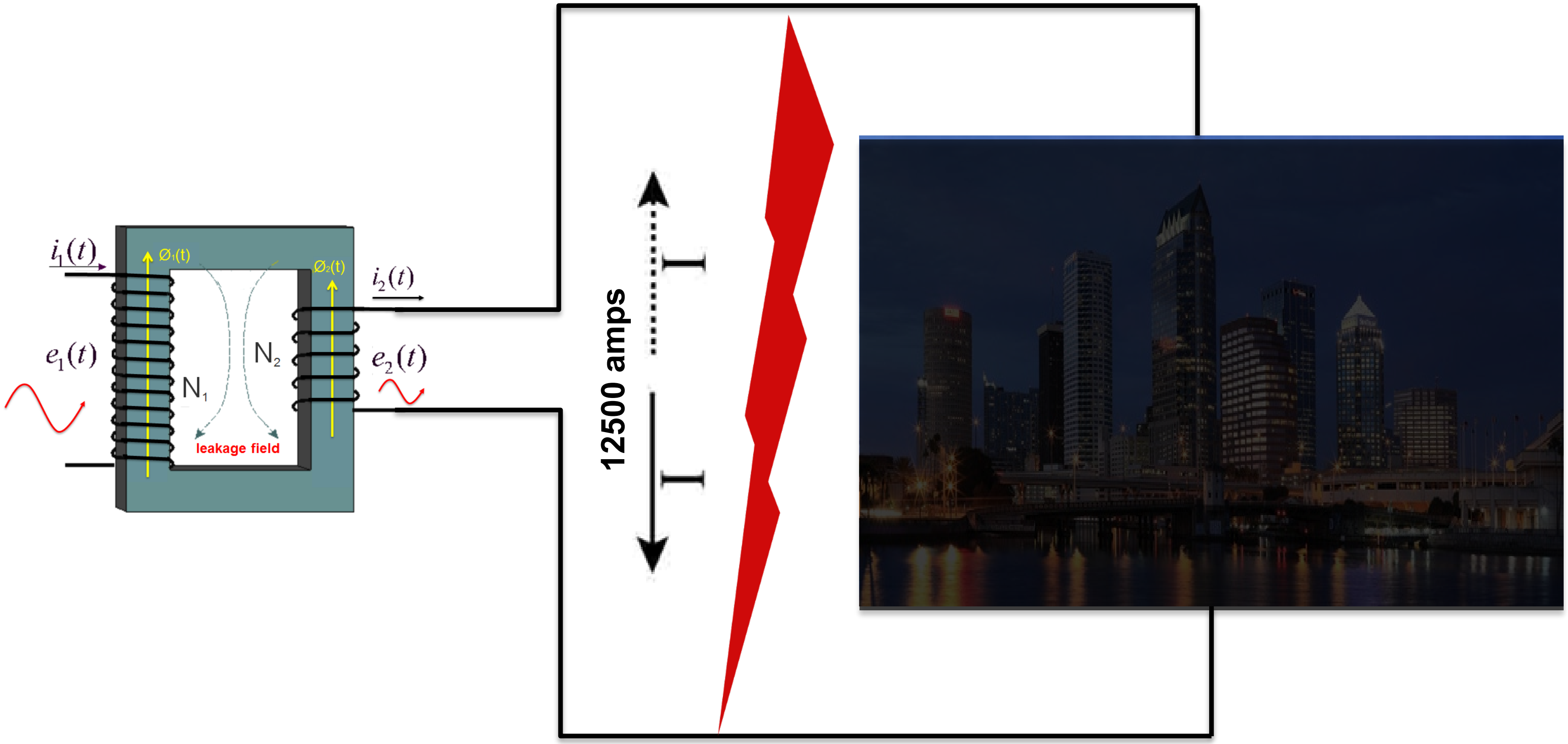
- An AC source supplies power to a given load (i.e. a city). A complete circuit has a source, with power entering a load and returning to the source. Amount of current that flows is directly related to the load on the transformer.



# 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

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

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

$\phi$ 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

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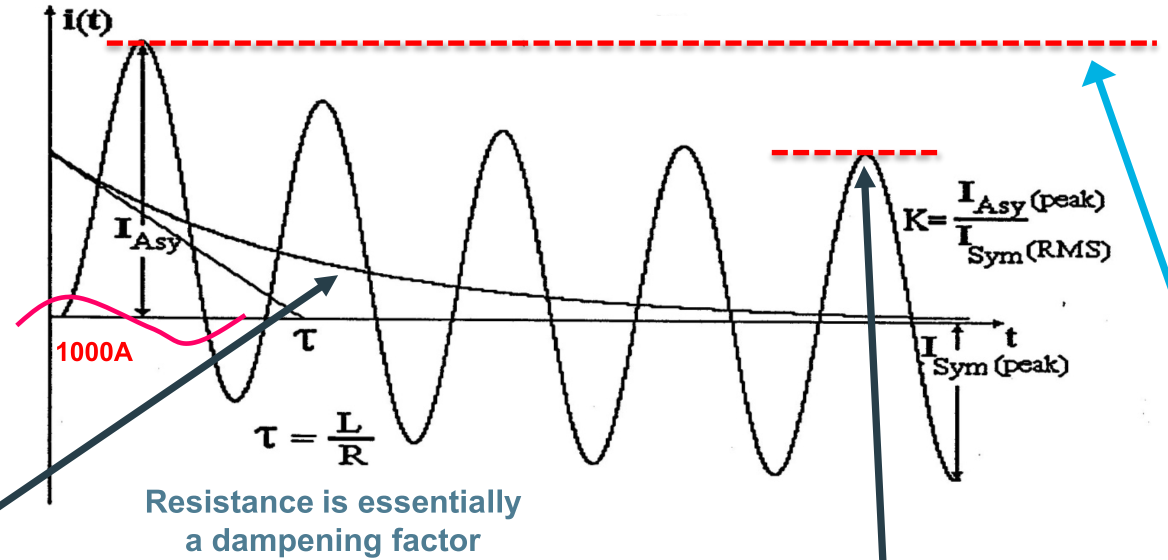
(Symmetrical and Asymmetrical)

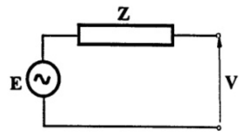
The fault current within a transformer will follow this typical exponential decay



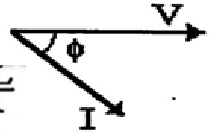

$$i(t) = I_{Sym} Sin(\omega t - \varphi) + I_{Sym} e^{-\frac{t}{\tau}} Sin\,\varphi$$

**Symmetrical (RMS) current**

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




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




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

**Asymmetrical (Peak) current**

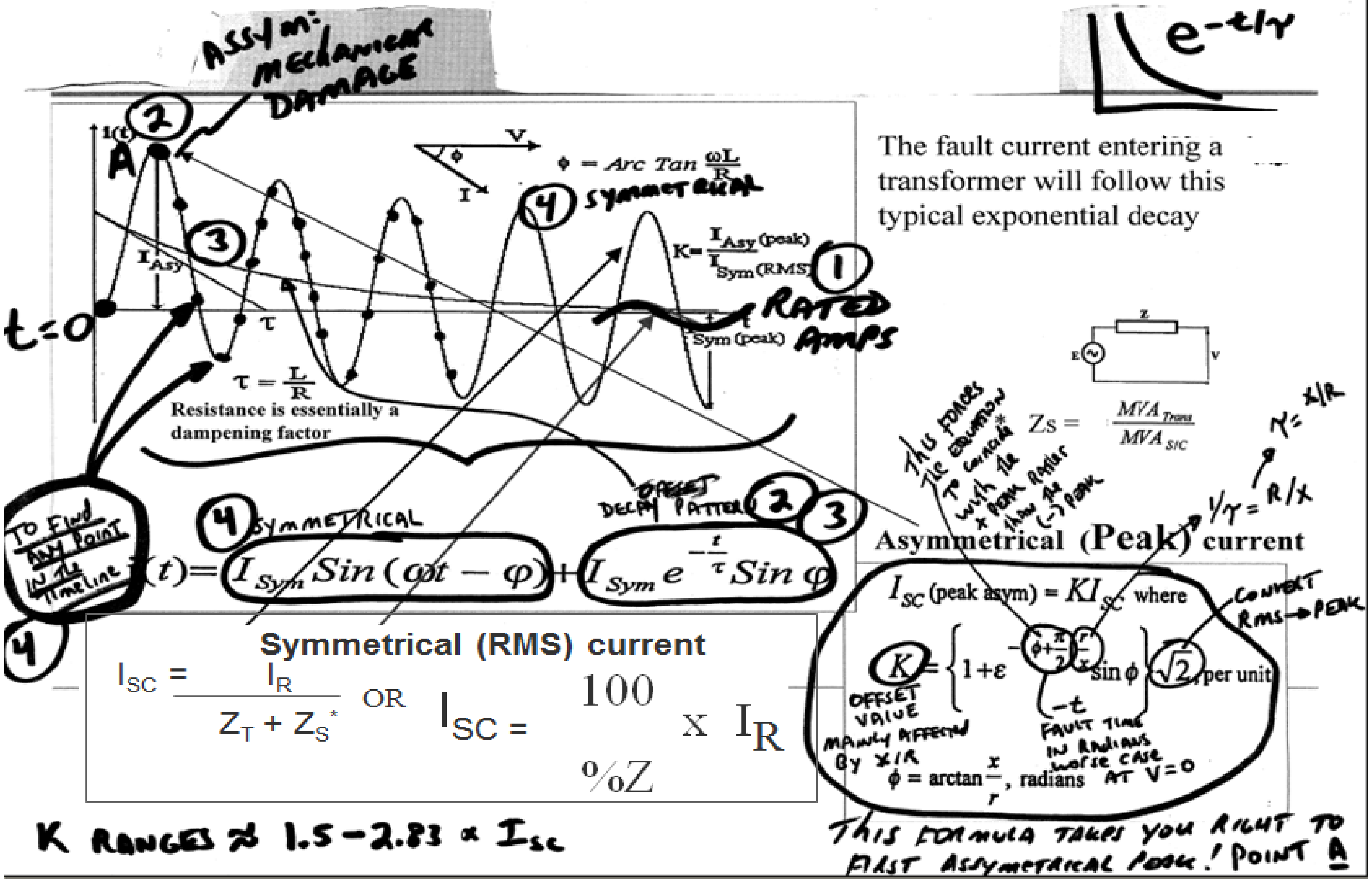
$$I_{SC}\,(\text{peak asym}) = KI_{SC} \text{ where}$$

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

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

Say Z were to be 8.0%, then: Isc would be 12.5x normal rated current

# Different Parts of the Formulas…



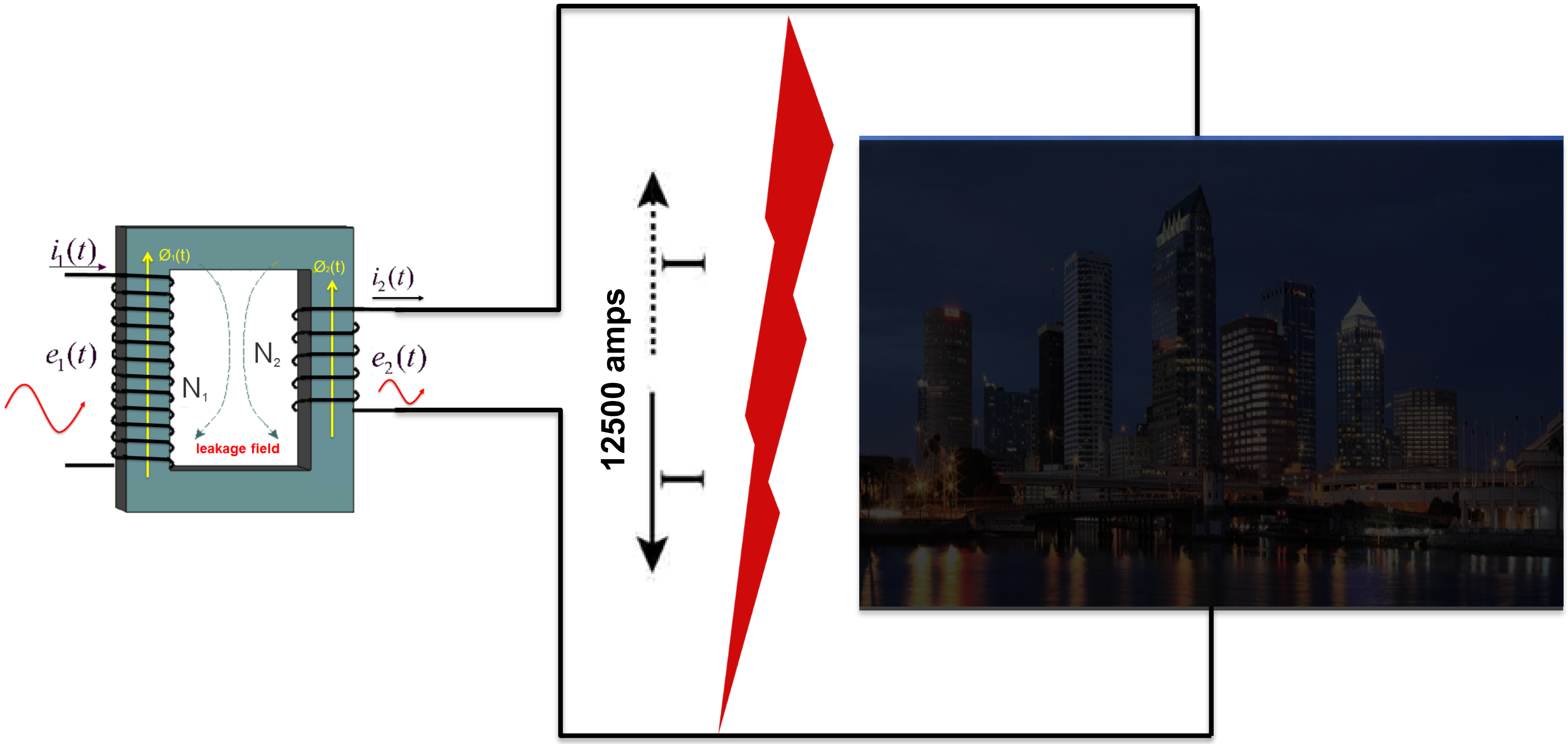
Part 4 – Visualization of the Magnetic Forces:

- Axial Forces on Winding Conductors (and other components)
- Radial Forces on Winding Conductors
- Combination of Axial/Radial Forces

# 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.

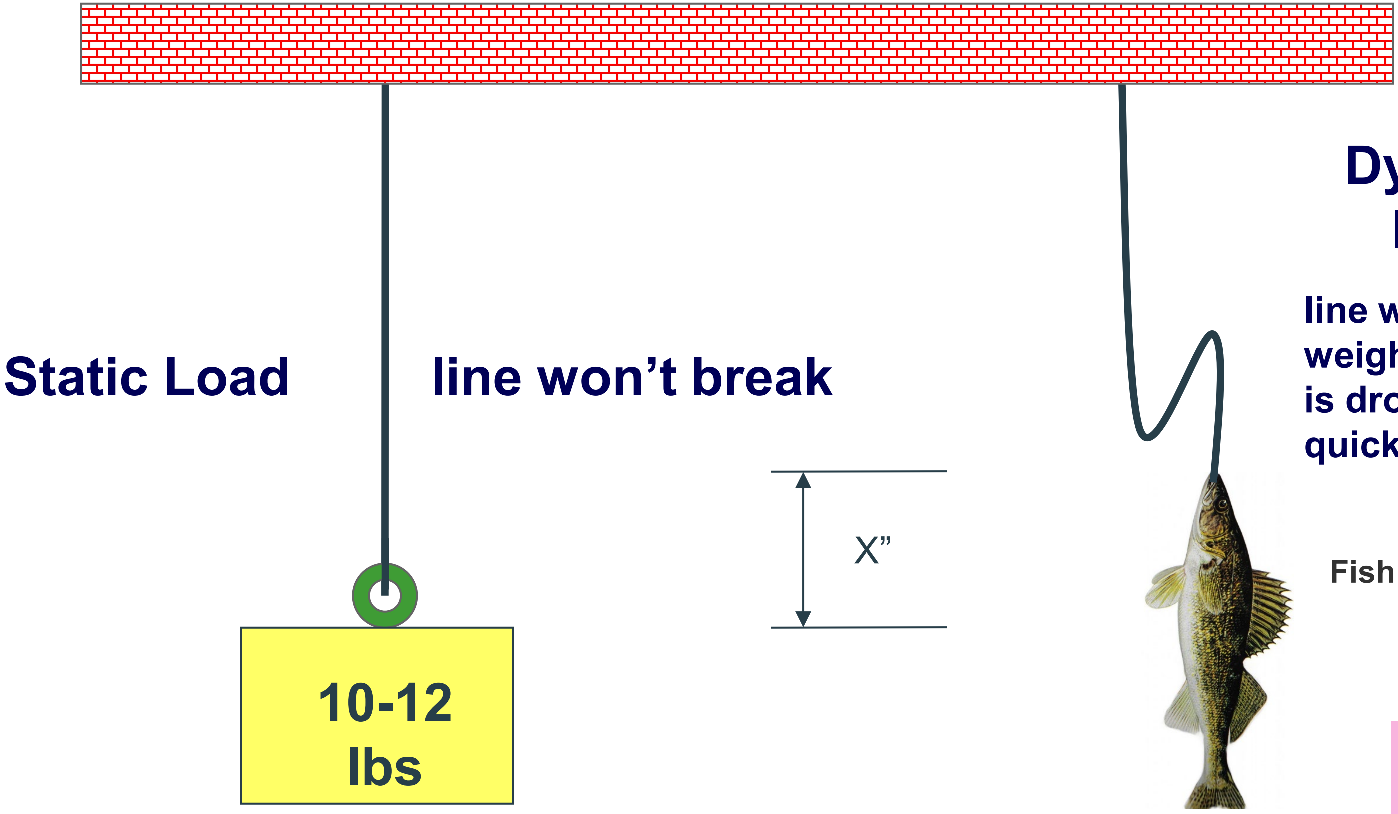
Short circuit forces are all acting in 3-D (combination of axial/radial/angular).

They can reach summative 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




**Dynamic Load**

**line will break at smaller weight levels when weight is dropped or line is quickly pulled or stressed**

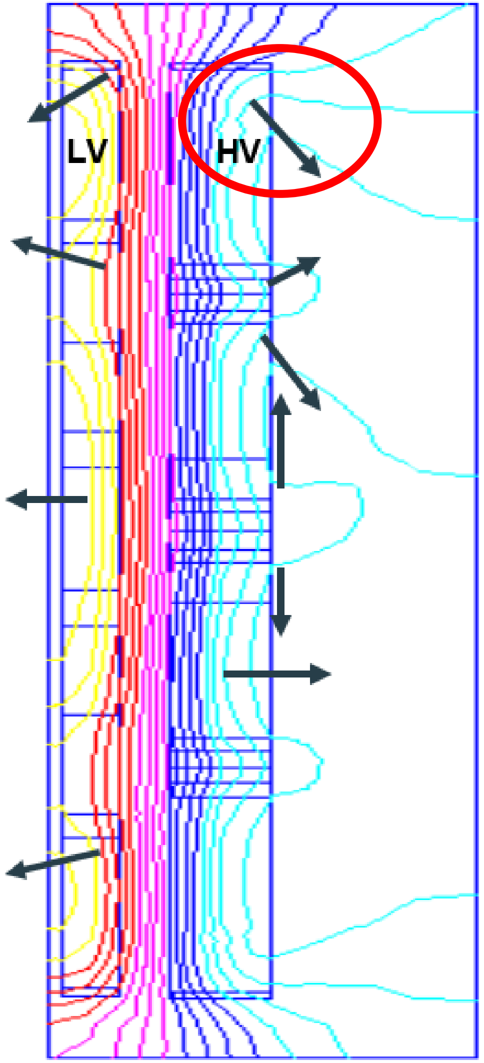
**Fish that got away:  Approx 6 lbs**

**Some people have been able to catch a large “musky” on 2 lb test line**

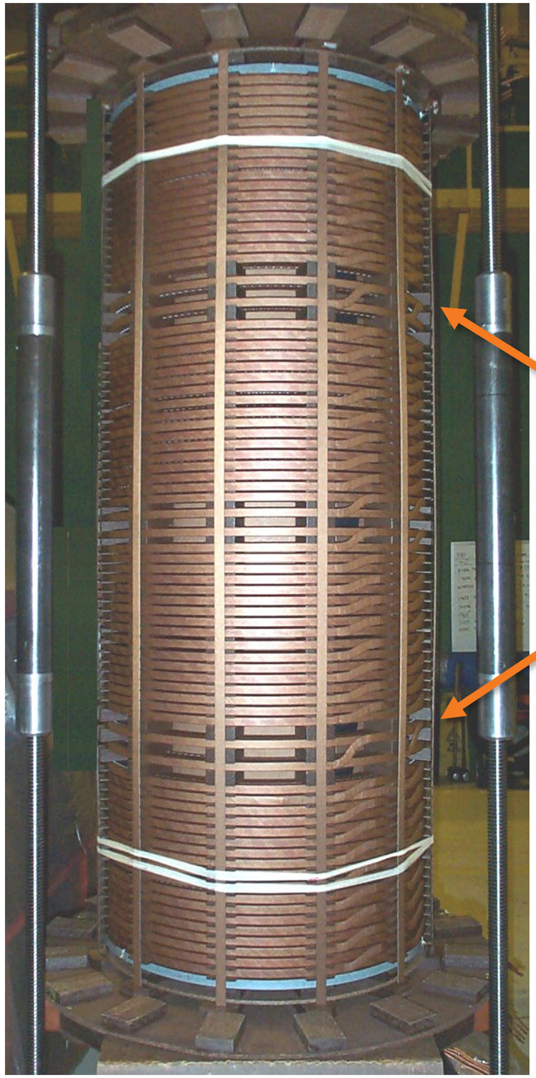
# Visualization of Magnetic Fields and Forces

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**

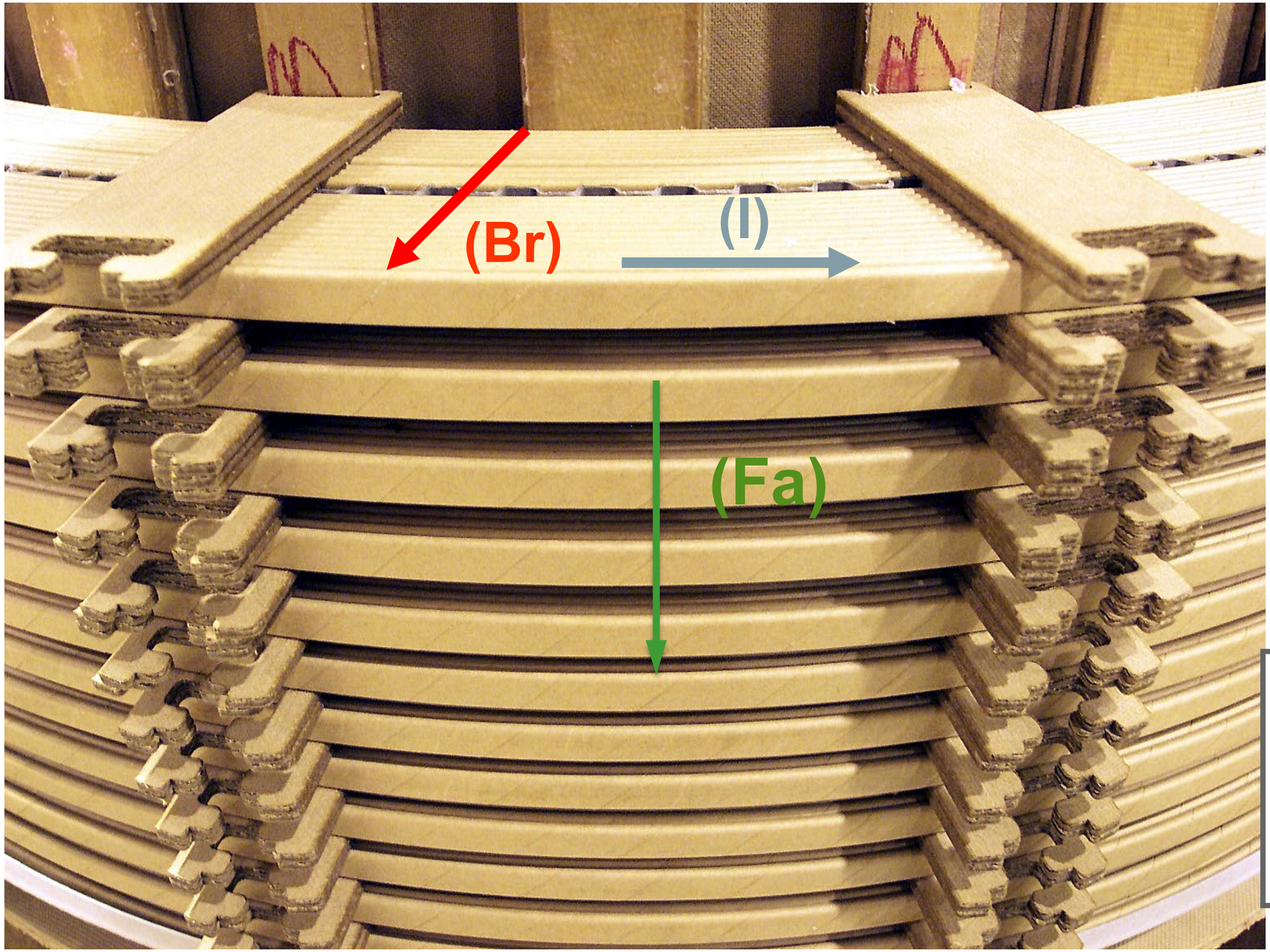



**Finite Element Analysis of Leakage Flux Between Coils**



**Axial locations of where HV DETC taps are located**

# Axial Forces - (Applying Left Hand Rule)




Current (I)

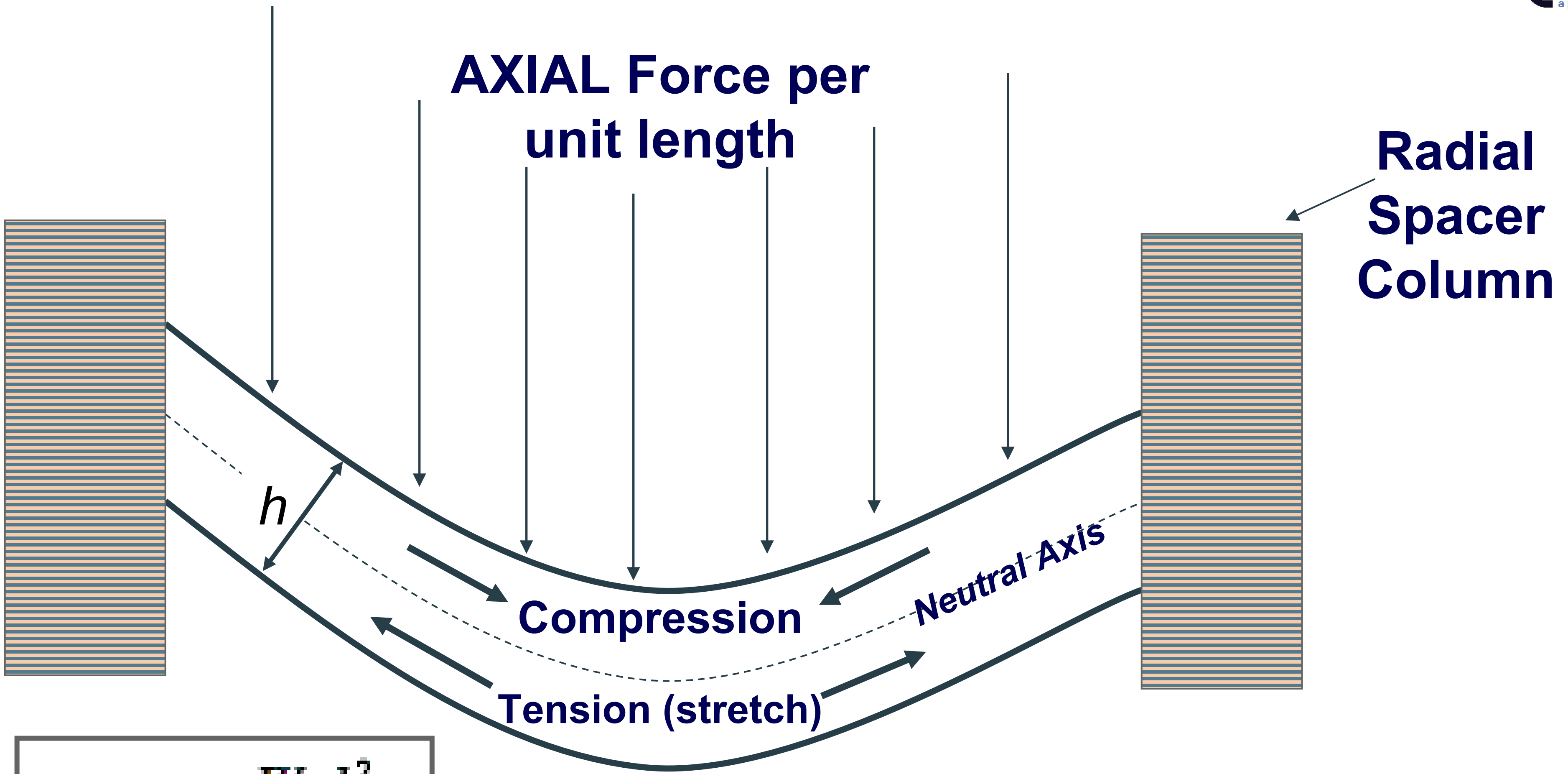
Flux (B)

Force (F)

**Length of beam:**

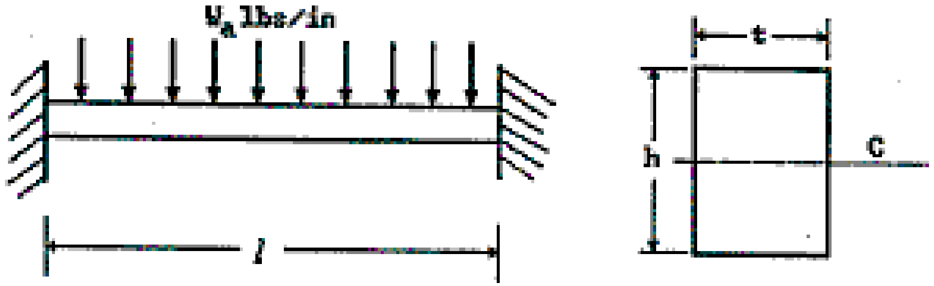
$$l = \frac{2\pi R_{OD}}{m} - W_{ks}$$

# Beam Bending Under Load (elevation view)




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

# Beam Bending Stress




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

**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)

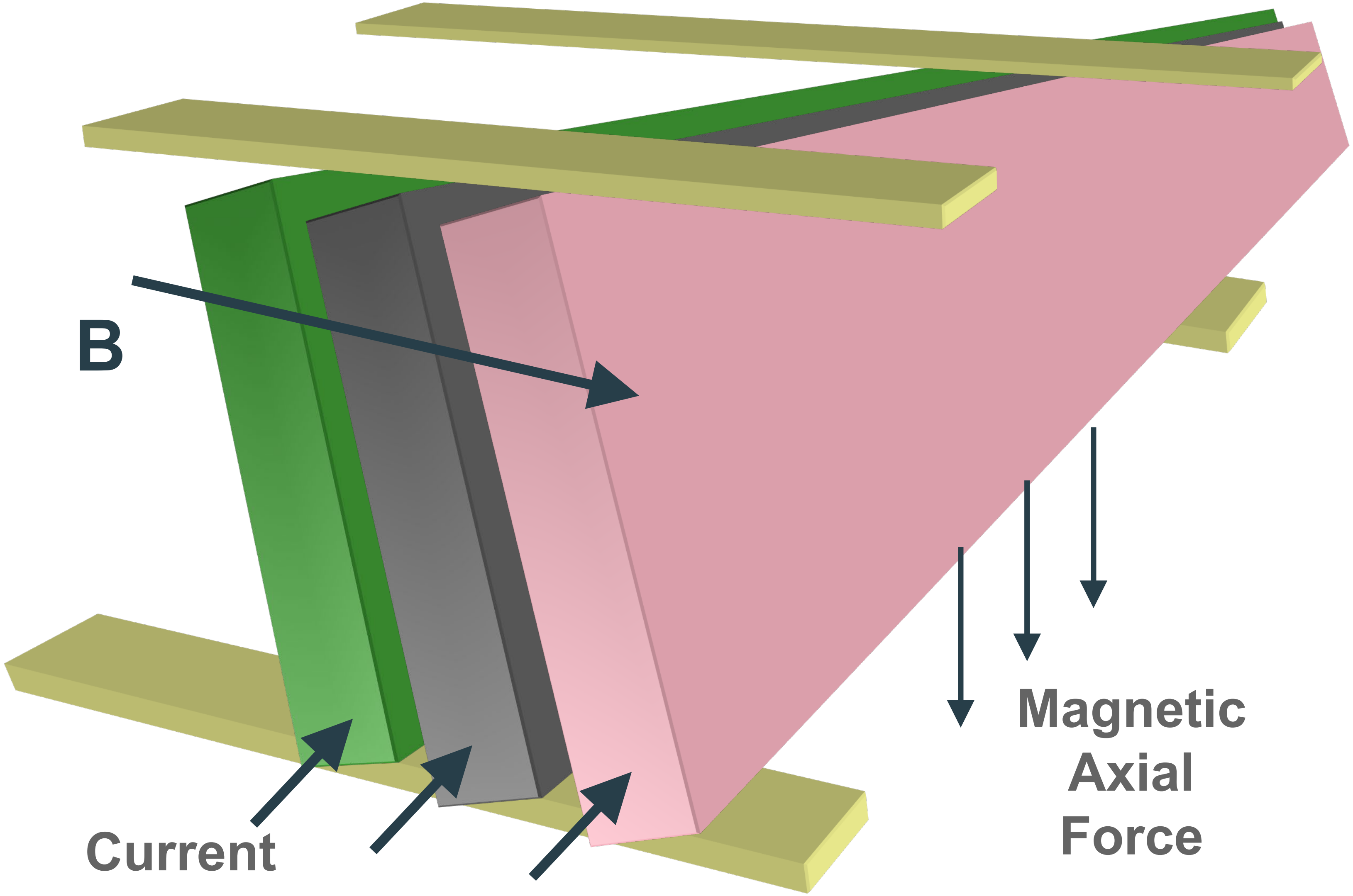
**Length of beam:**

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

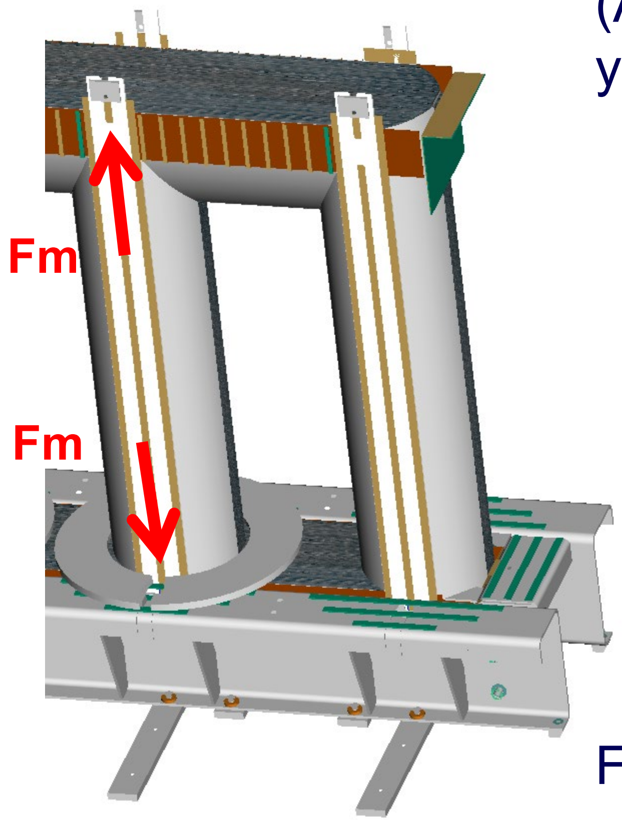
**Linear Load:**

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

# 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.

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

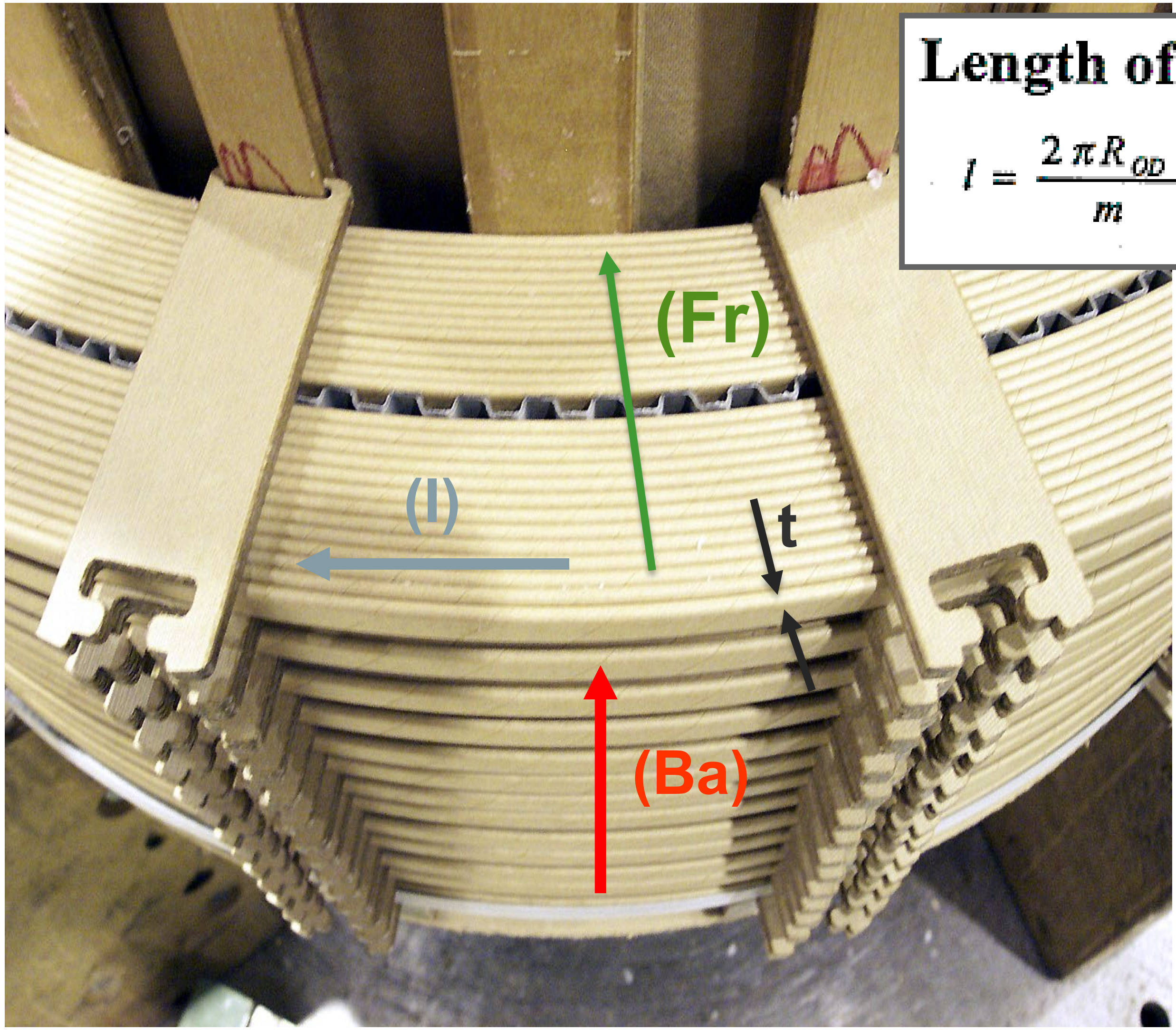
Yield Strength of Tie Bar = 100,000 PSI

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)



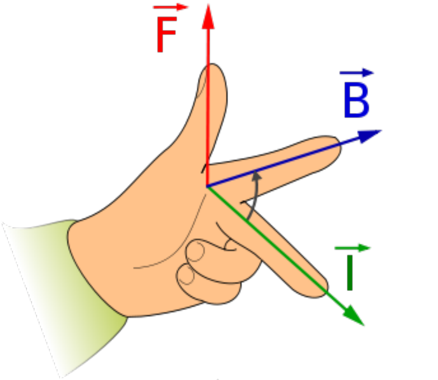

**Length of beam:**

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

Current (I)

Flux (B)

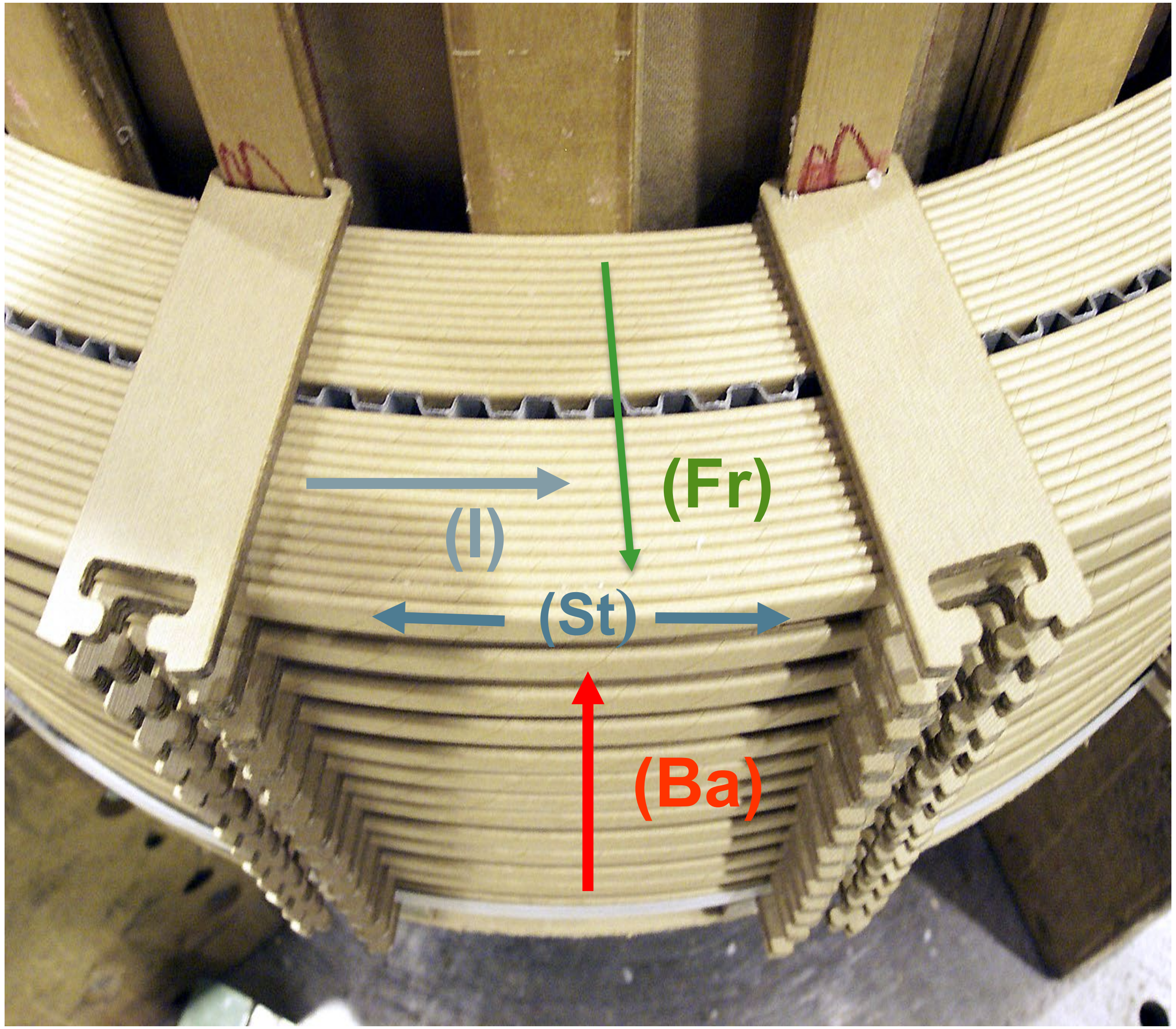
Force (F)




Left-Hand Rule

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

# OUTWARD Radial Forces – Hoop Stress (outer coil)

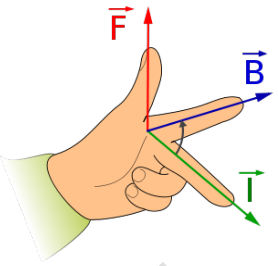



Current (I)

Flux (B)

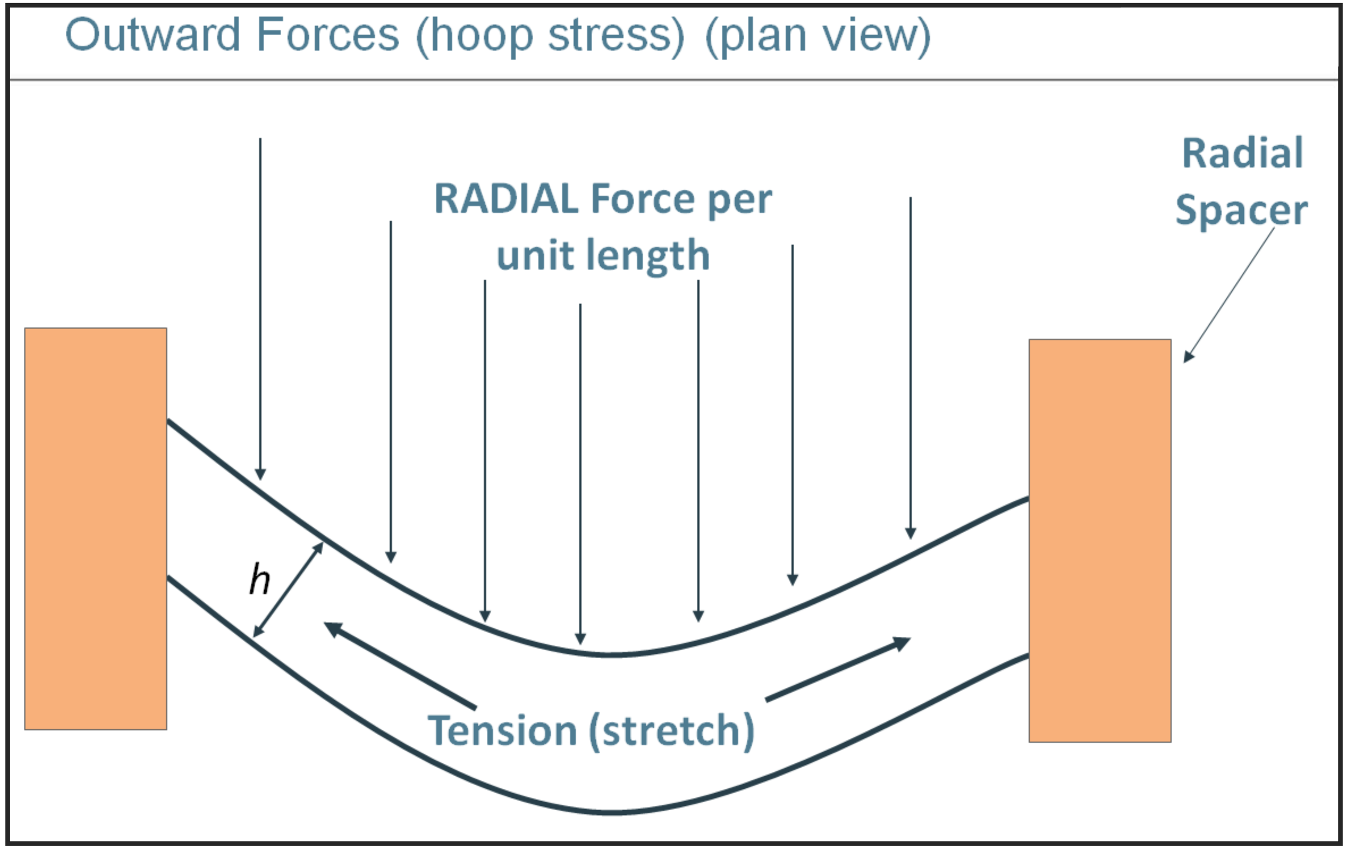
Force (F)

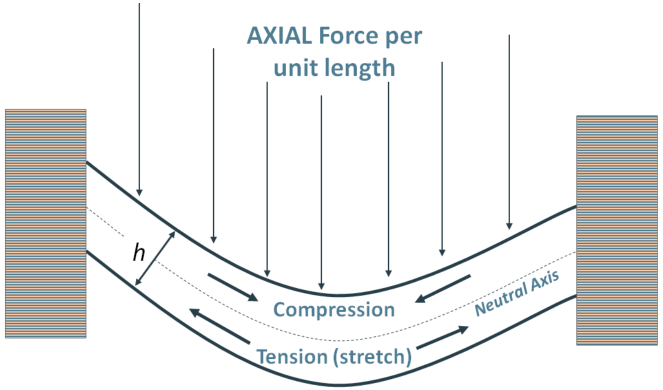
Tensile Stress (St)




Left-Hand Rule

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

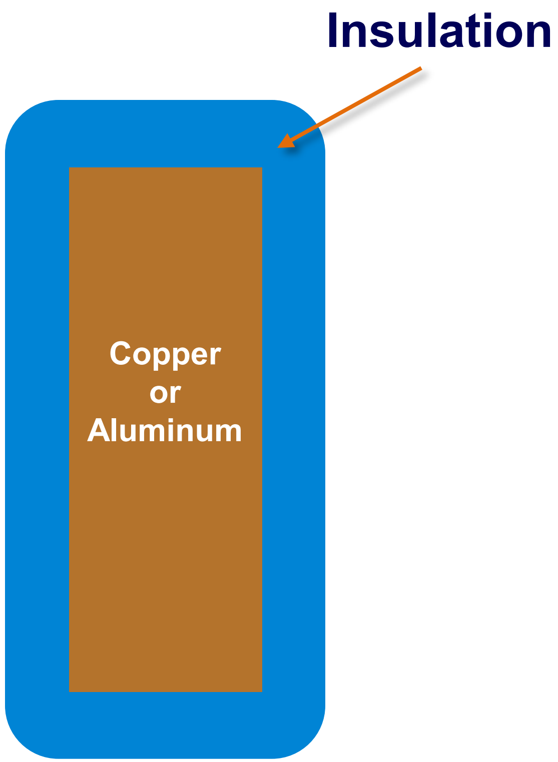



**No neutral axis**

# 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 C57.12.00-2000 section 7.4.




Insulated Conductor

# Winding Temperature During a Short Circuit

Approximate method:

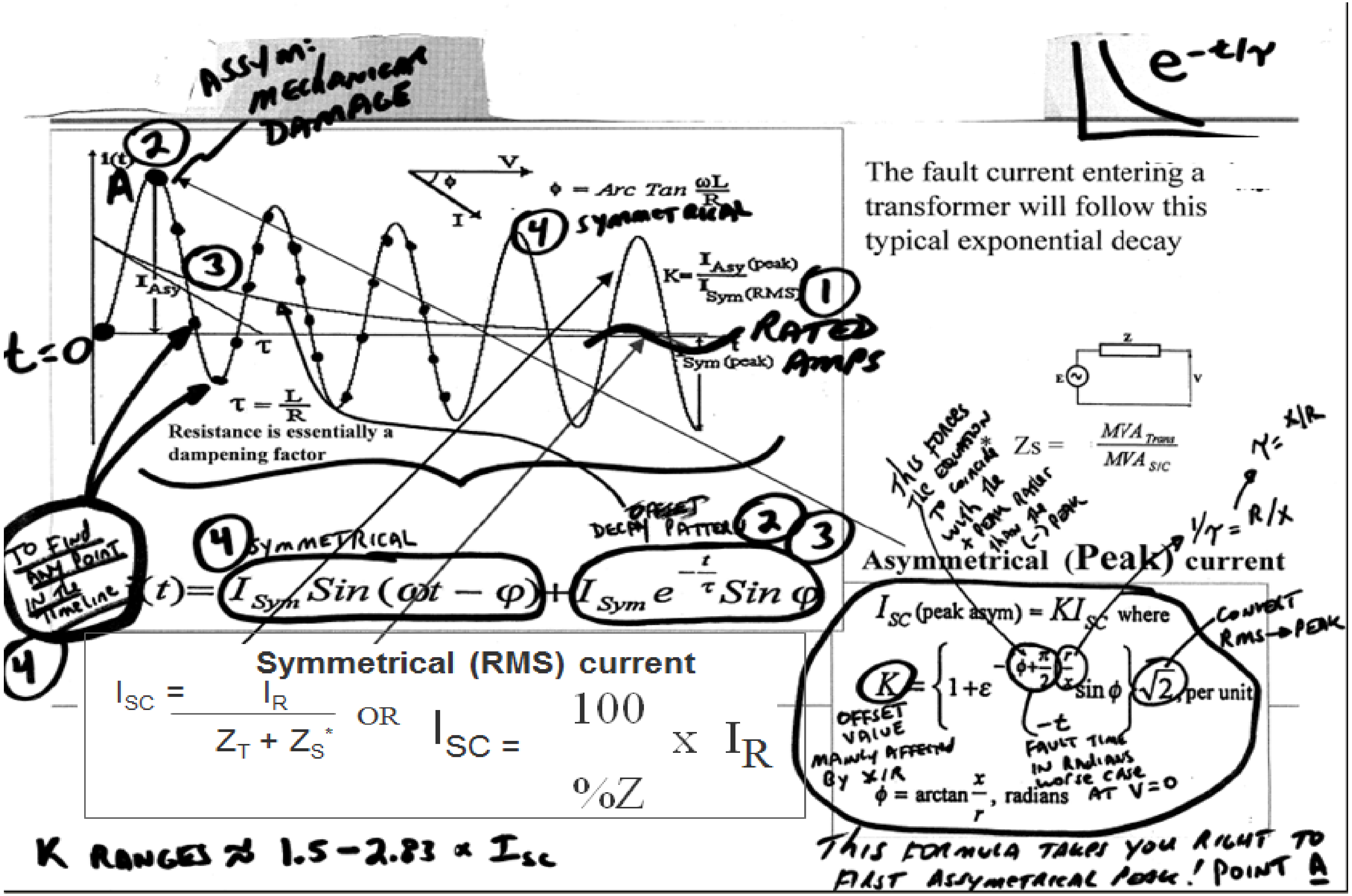
$$T_f = \frac{(S_{\Delta k})^2 t}{K_m} + T_{OR} + T_a$$

$T_f$ = 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 current density at symmetrical short circuit current (W/dm$^2$)
$t$ = short circuit duration (s).
$K_m$ = 156 for copper / 73 for EC grade aluminum

# Part 5 – Calculation Example:

- Calculate short circuit current and asymmetrical offset factor

# Back to our formulas again….



# 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% (= 0.8 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 (asymetrical) “K” factor)
3. Apply derived data from 1. and 2. to determine peak offset asymetrical amps.

Next

# Example of How to Calculate SC Current

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

Note: $Z_T$ and $Z_s$ are in p.u.

**Symmetrical Current without Zs**

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

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

*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**

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

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

$$Z_s = \frac{MVA_T}{MVA_S} = \frac{30}{9800} = 0.31\%$$

$$I_{SC} = \frac{1000}{0.08 + 0.0031} = 12{,}034\ A$$

*Note: Zs is derived from C57.12.00-2010 Table 15 if not specified from customer.*

Difference (with vs without Zs) is almost 500A or 4%

Next

# Example of How to Calculate SC Current

## 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

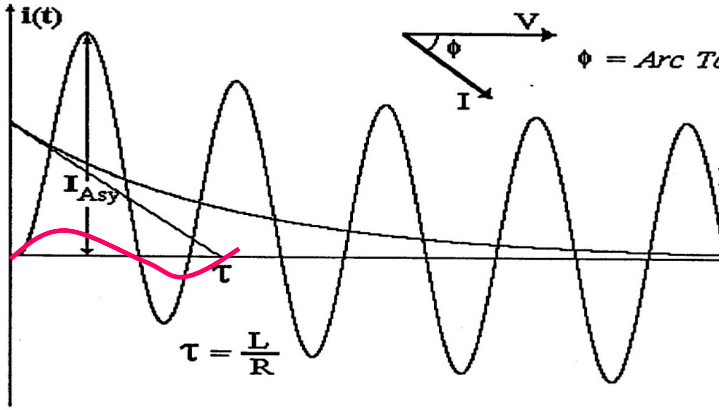
# Example of How to Calculate SC Current

## 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

## 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 amps / 1000 amps)$^2$ = (33.75)$^2$ = 1140 x normal forces**

# Questions

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## Contact

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