FLUXTROL®

Advanced Induction Materials and Technology

Online Induction Heating Course

1a. Basics of Induction Technique Part 1

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What is Induction Heating?

Induction Heating is a Contactless Heating Method of bodies, which absorb energy from an **Alternating Magnetic Field**, generated by Induction Coil (Inductor)

There are two mechanisms of energy absorption:

- generation of close-loop (eddy) currents inside the body which cause heating due to electrical resistance of the body material

- hysteresis heating (for magnetic materials ONLY!) due to a friction of magnetic micro volumes (domains), which rotate following orientation of external magnetic field

Eddy Current and Hysteresis Heating

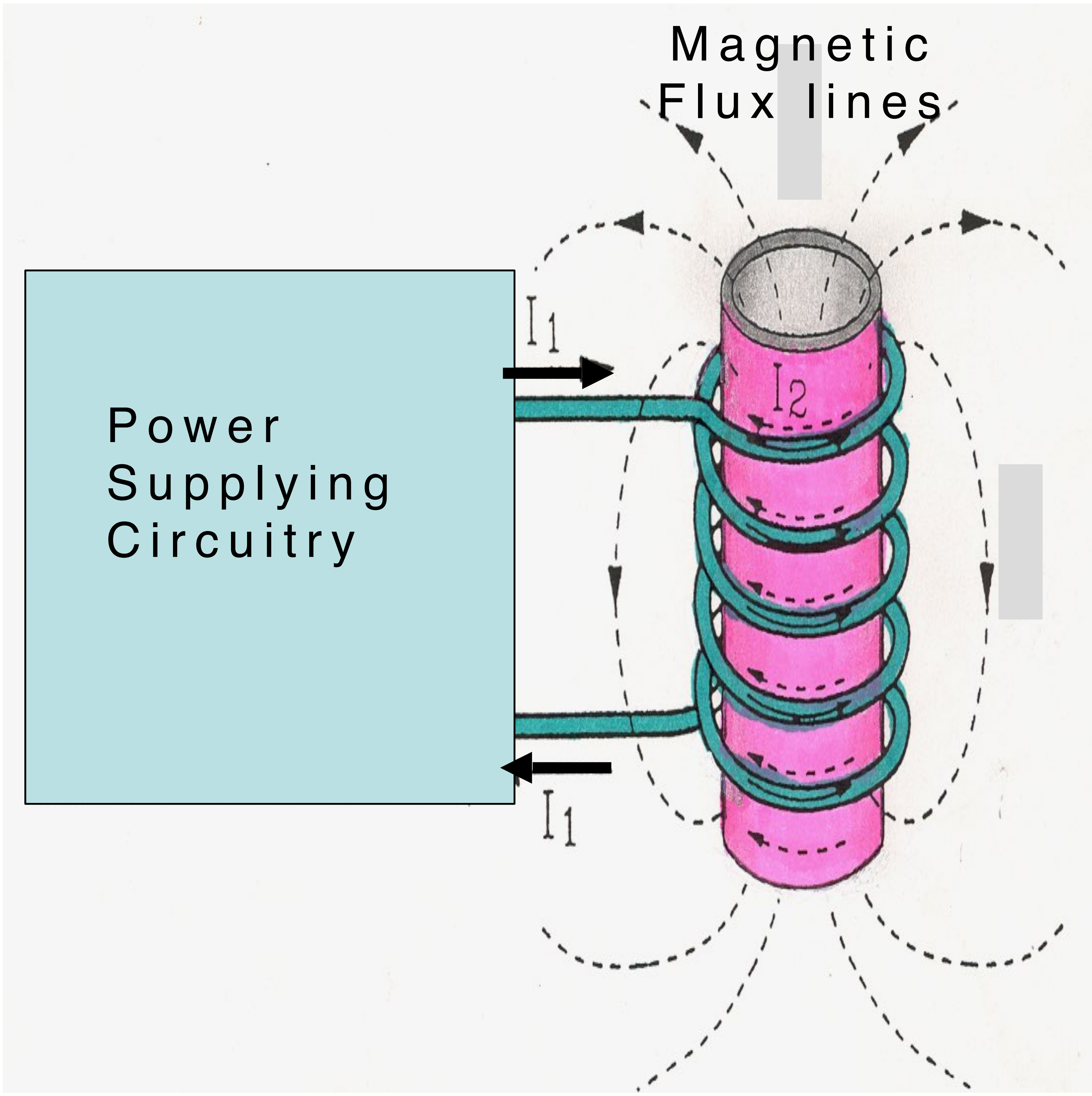
Eddy current heating occurs in all conductive materials (magnetic or non-magnetic steels, copper, aluminum, graphite, molten glass or oxide etc.) when they are placed in an alternating magnetic field. Eddy currents always flow in a closed loop (law of nature!) and for effective heating there must be a good path for current to flow in the part to be heated. For example, it is easy to heat a wire loop but almost impossible to heat a thin wire then the loop is open.

Hysteresis heating is zero in non-magnetic materials (aluminum, copper, hot steels) or responsible for a small percentage of heat generation in compact magnetic bodies (mainly steels at low or middle temperatures). However, in magnetic materials composed of particulates (including magnetic flux concentrators) hysteresis may be the major source of heat generation. Each particle is heated individually and the workpiece may have any shape and size (massive bodies, strips, films, wires).

Principles of Induction Heating

Chain of phenomena:

1. Power supply delivers current (I1) to induction coil
2. Coil currents (ampere-turns) generate magnetic field. Lines of field are always closed (law of nature!) and each line goes around the current source – coil turns and workpiece
3. Alternating magnetic field flowing through the part cross-section (coupled to the part) induces voltage in the part
4. Induced voltage creates eddy currents (I2) in the part flowing in direction opposite to the coil current where possible
5. Eddy currents generate heat in the part



Principles of Induction Heating (cont.)

- There are three closed loops in any induction device:

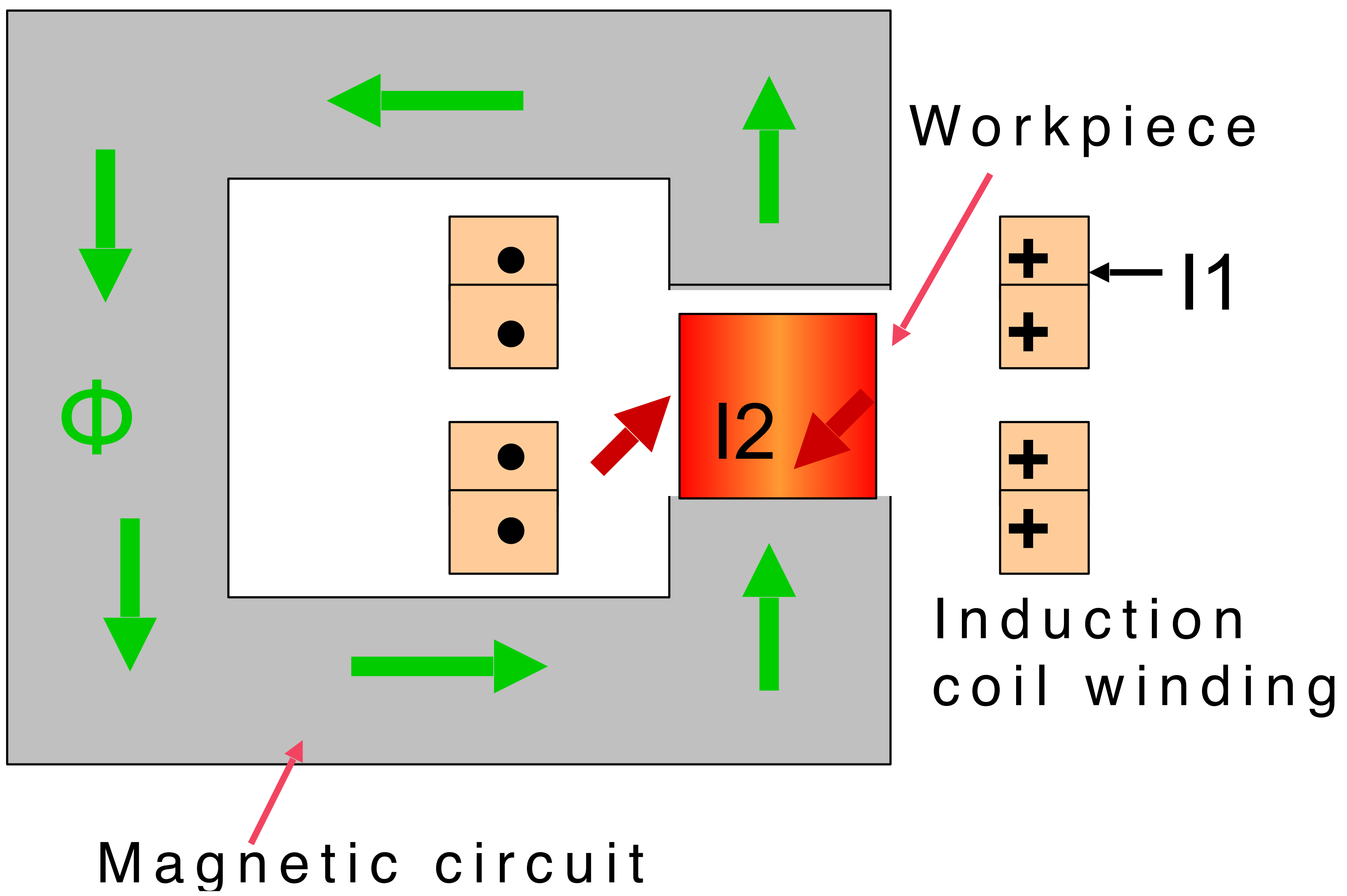
  Coil Current (I1) Loop

  Magnetic Flux (Φ) Loop

  Eddy Current (I2) Loop

- Magnetic Flux Loop may be "materialized" as a magnetic core in transformer-type induction system (right) or be invisible (in air or other surrounding media)

- Magnetic Flux Loop is very important because that is where we can install magnetic Flux Controller to improve heating



Magnetic Field Lines

Magnetic field lines represent lines of magnetic flux density B.

Magnetic lines "visualize" magnetic field. More dense concentration of magnetic lines corresponds to higher flux density.

Lines are always closed around their source (currents).

In induction systems the coil current changes during each cycle from a maximum to zero, to a maximum in opposite direction, to zero again and to an initial maximum value. When frequency is 1000 Hz, a period is 1/1000 sec.

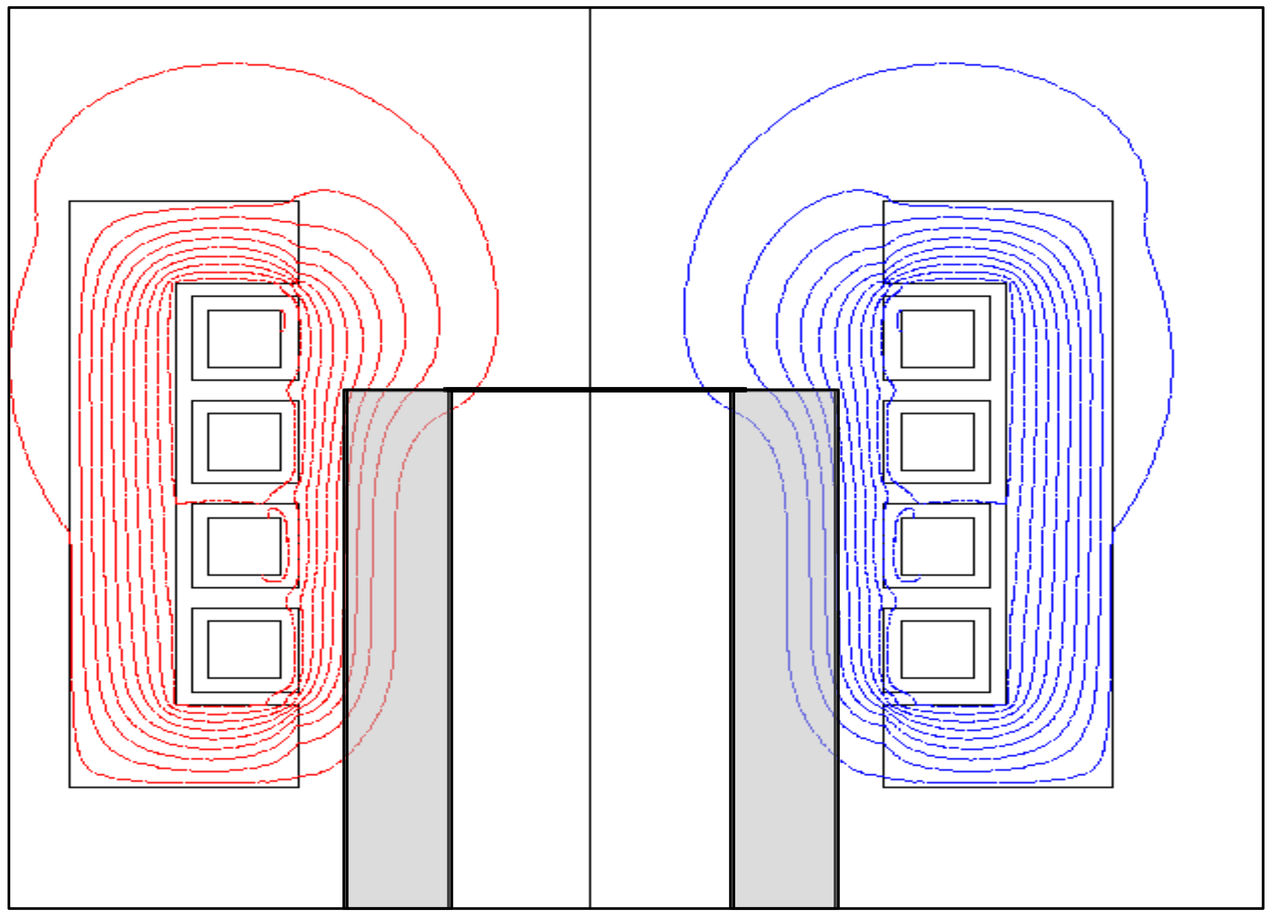
Pattern of magnetic lines changes dramatically at any instant inside of each period.

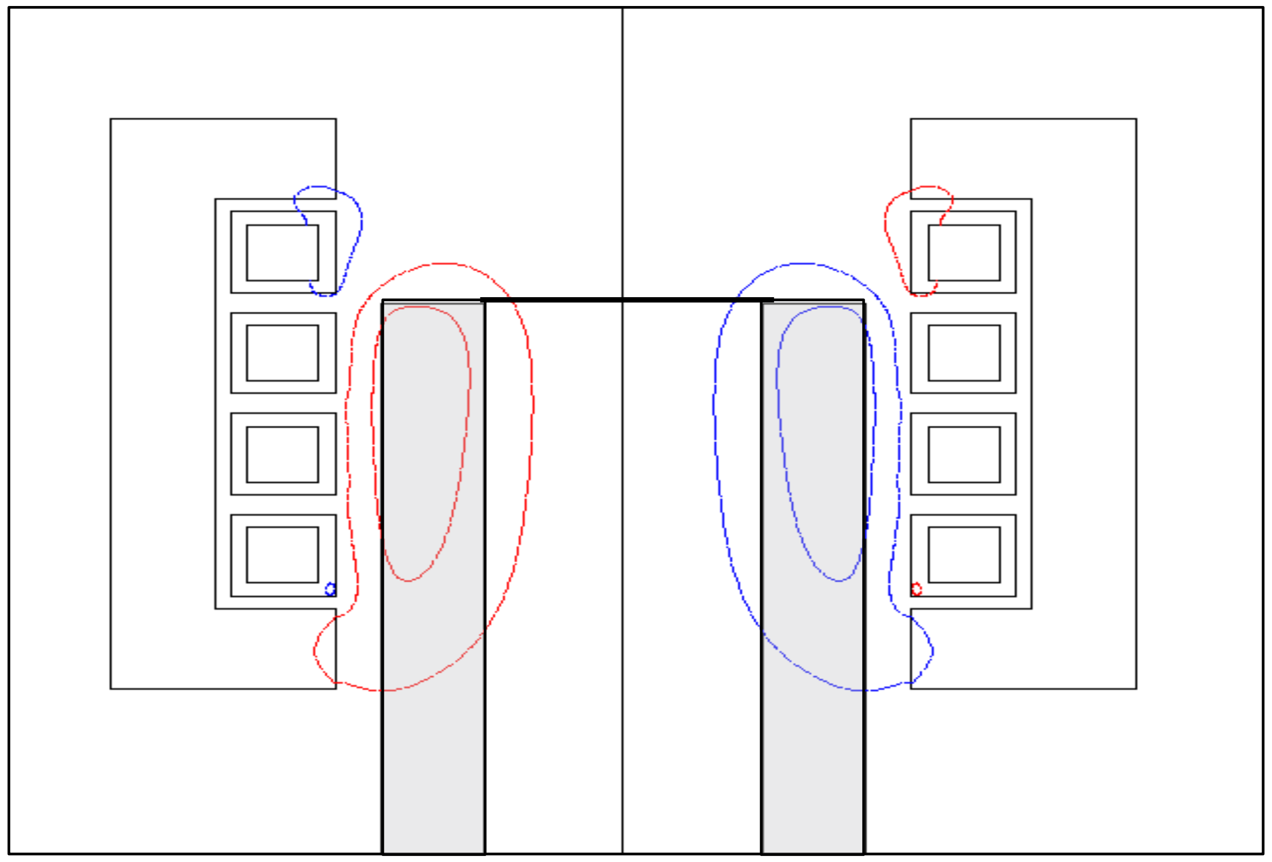
Example: Heating of an end of non-magnetic tube in a 4-turn inductor with a concentrator.

Top picture – magnetic field pattern when an instantaneous value of a current in the coil is maximum. Blue lines are directed clock-wise; red – counter-clockwise.

Bottom picture – instantaneous current in the coil is close to zero and magnetic field is created mainly by eddy currents that continue to flow in the tube.

Magnetic line pattern is very essential for analysis of computer simulation results; visualization of lines at incorrect instant can cause misinterpretation of the results.





Electromagnetic Processes in Induction Installation

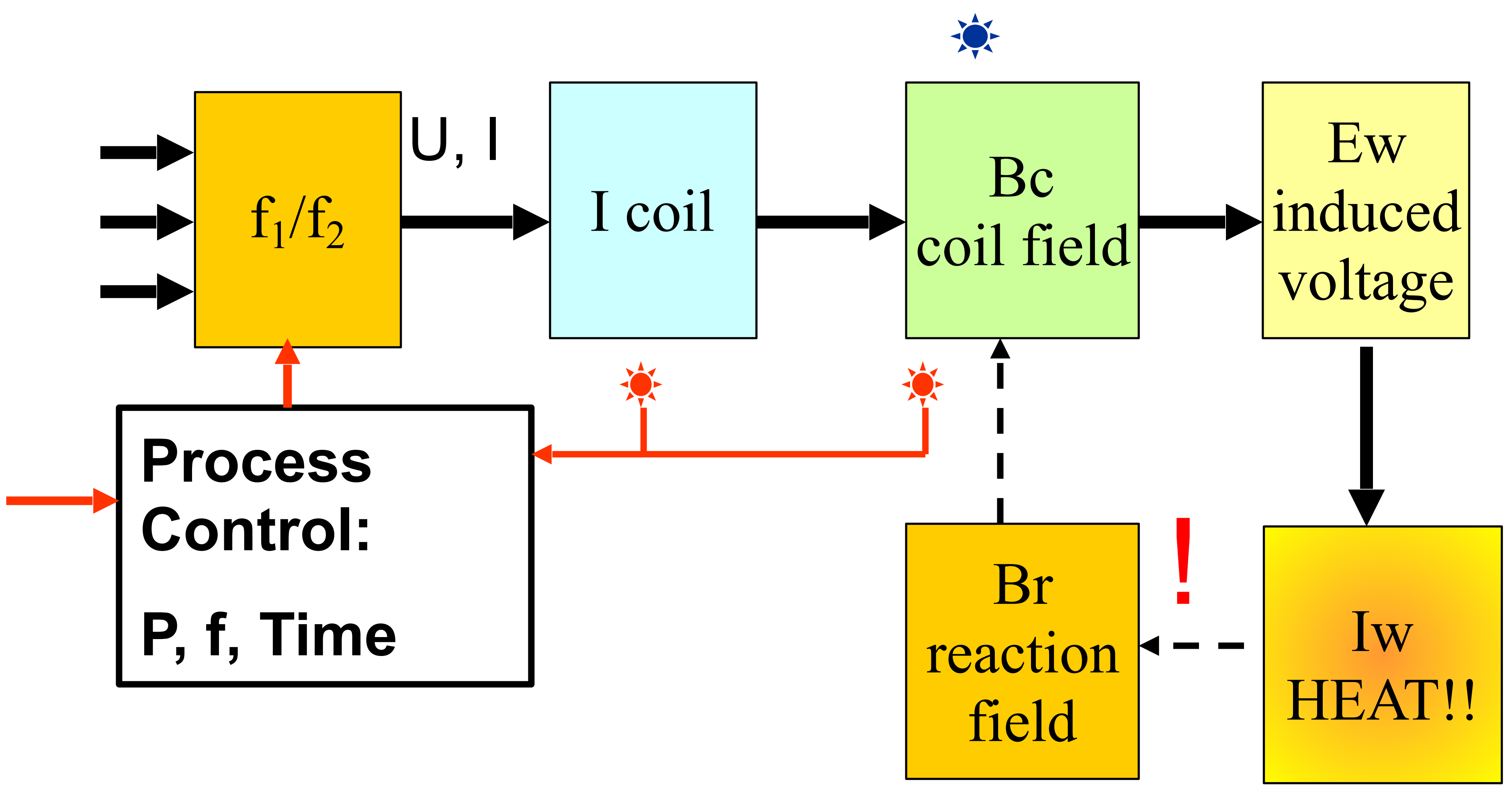
f1/f2 – frequency converter (power supply)

Bc – magnetic flux density (induction) created by coil

Ew – voltage induced inside the workpiece, which causes eddy current Iw flow

Br – flux density of the reaction field, which is "back-coupled" to the coil

Br causes variation of the coil parameters in the process of heating when workpiece properties vary with temperature



Point of magnetic flux control

Points of Feedback signals that may be used for close-loop control and process monitoring

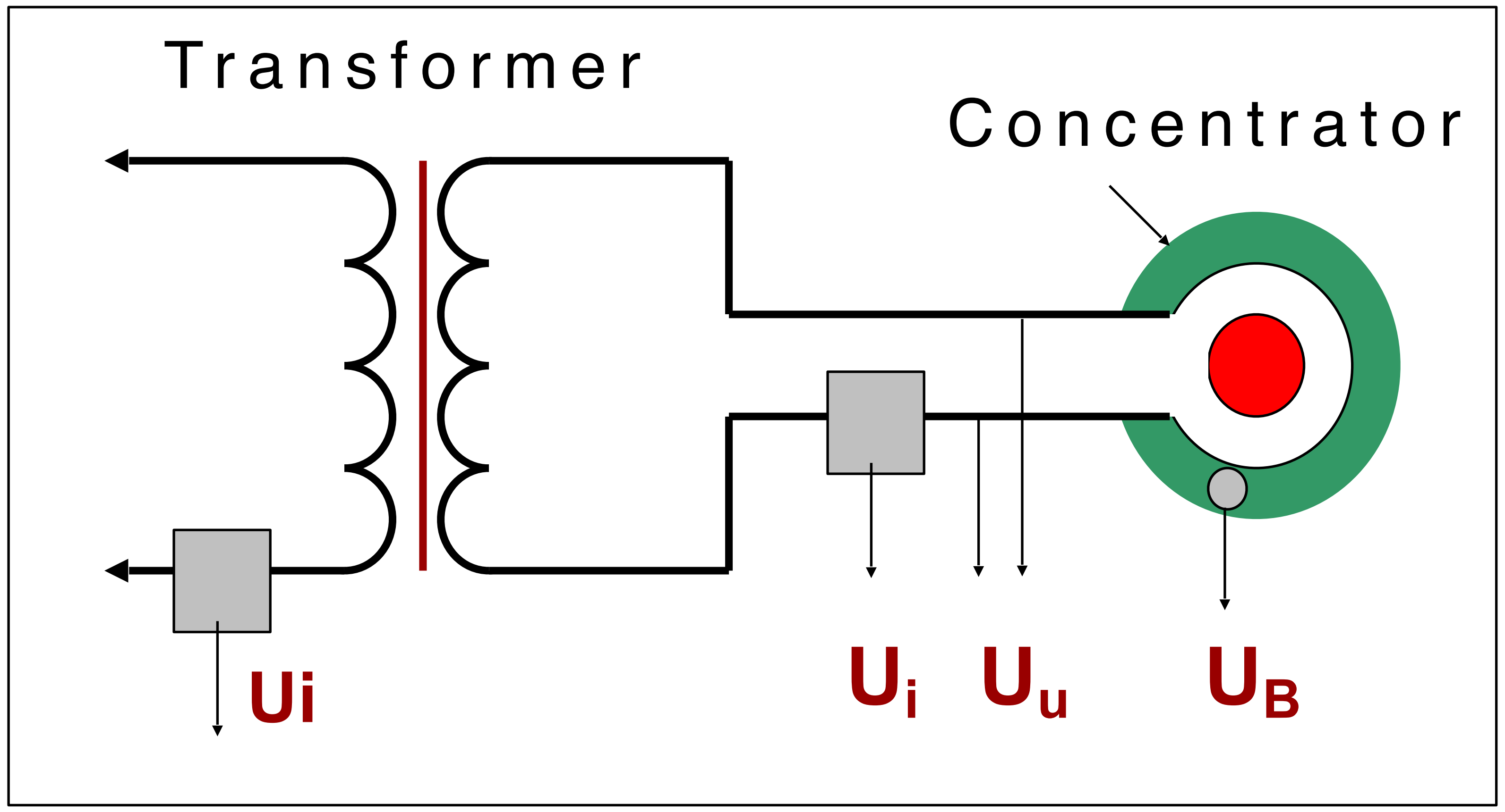
Layout of Induction Circuit with Sensors

Coil current and voltage signals are widely used for process monitoring or control.

Modern power supplies may be set to operate at constant coil voltage, current or generator power.

Signal U_B, which is proportional to magnetic flux density in a certain point of the coil, may be used for monitoring of local heat intensity and part positioning. For example this signal may determine Off-Center position of the part or crack on its surface.

Corresponding sensor may be incorporated in magnetic concentrator.



Ui – Current Signals

Uu – Voltage Signal

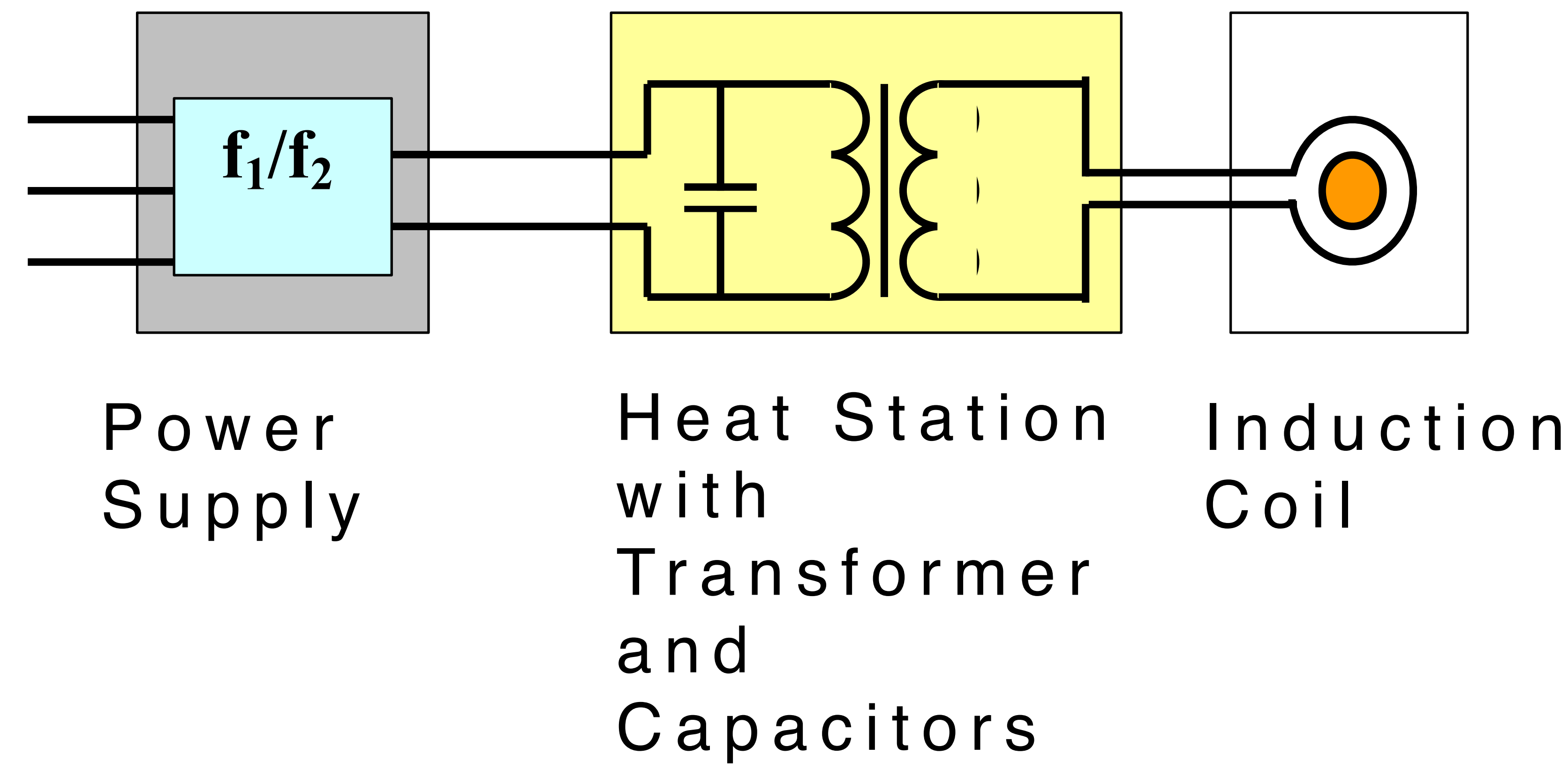
U_B – Flux Density Signal

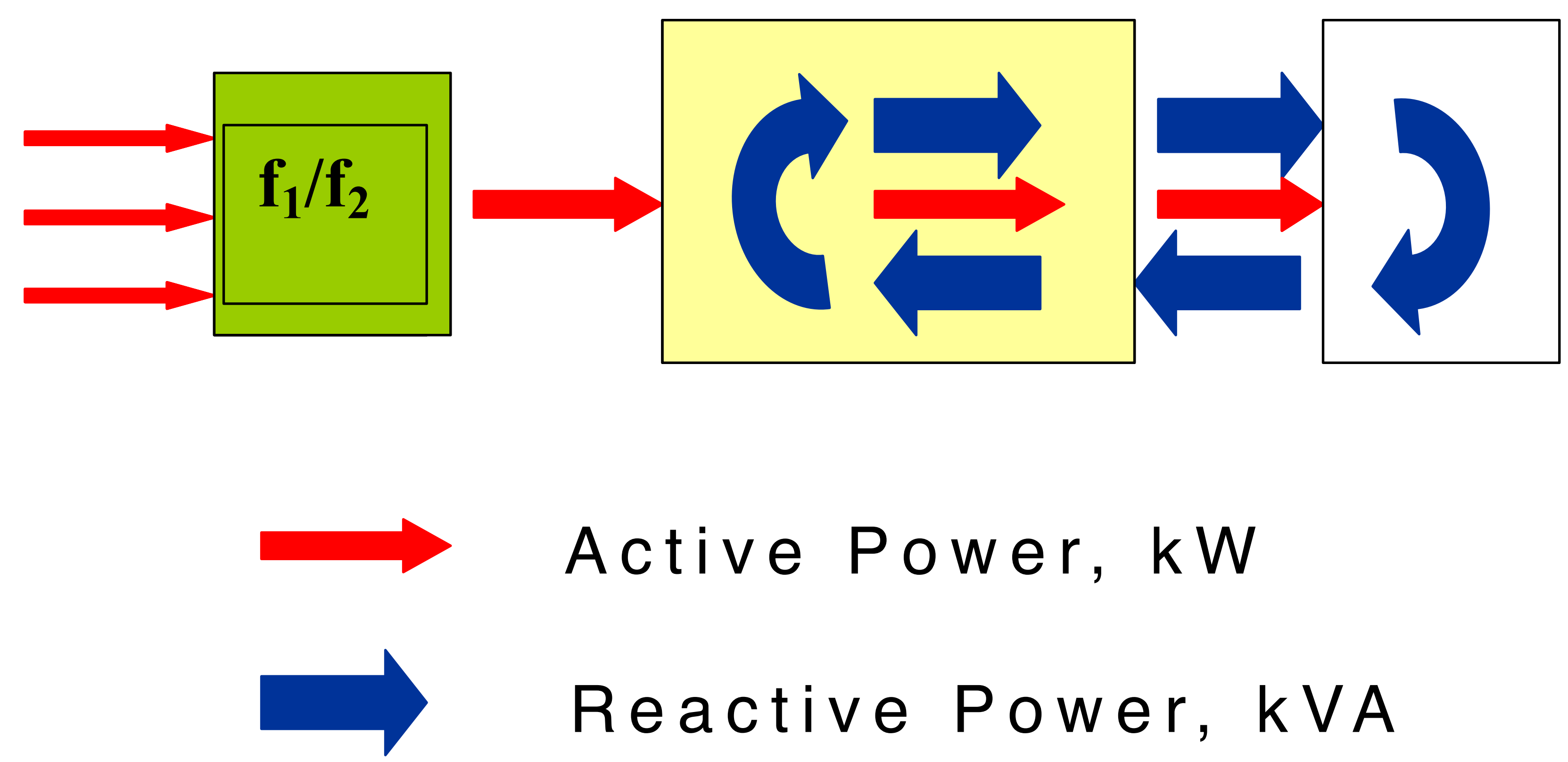
Power Flow in Induction Heating Installations

Alternating current changes direction twice during each frequency cycle. If frequency is 1kHz, current changes direction 2000 times in a second.

A product of current and voltage gives the value of instantaneous power (p = i x u), which oscillates between the power supply and the coil. Power is being partially absorbed (Active Power) and partially reflected (Reactive Power) by the coil. Capacitor battery is used to unload the generator from the reactive power. Capacitors receive reactive power from the coil and send it back to the coil supporting oscillations.

A circuit "coil-transformer-capacitors" is called Resonant or Tank Circuit.





Theory of Induction Heating

- Induction heating is based on several physical phenomena – electromagnetism, heat transfer, metallurgical transformations etc.
- Traditional practice of induction system design is based on basic knowledge of how induction works and on numerous rules, formulae and dependences developed experimentally or using theoretical methods (analytical or later numerical)
- More advanced procedure of induction system design is based on computer simulation
- Knowledge of induction heating physics and basic dependencies is imperative for induction system design and usage even when using computer simulation

Reference (Skin) Depth

Reference Depth is a fundamental value in theory and practice of induction heating.

Sometimes it is called **Penetration Depth** meaning that magnetic field penetrates to this depth from the surface of the workpiece and all the heat is generated inside of this layer. This statement is not accurate.

In reality, magnetic field, current and power **distributions** inside the body are different for different body shapes (flat, cylindrical, complex), size and material. They also depend on material property variation in depth due to magnetic saturation, temperature influence or material composition (multi-layer bodies etc.).

Depth δ (Greek letter Delta) is a **reference value** that depends **only** on material properties and frequency but does not account for body shape and size. For non-uniform materials δ is being calculated usually for properties on the body surface. Reference Depth is directly proportional to root square of material resistivity ρ (Greek letter Roh) and inversely proportional to root square of relative magnetic permeability μ (Greek letter Mu) and current frequency.

$$\delta = k\sqrt{(\rho/f\mu)}$$

Coefficient k depends on selected units

System	ρ	f	δ	k
Metric	μOhm-cm	kHz	mm	1.6
British	μOhm-in	kHz	inch	0.1

Reference Depth (cont.)

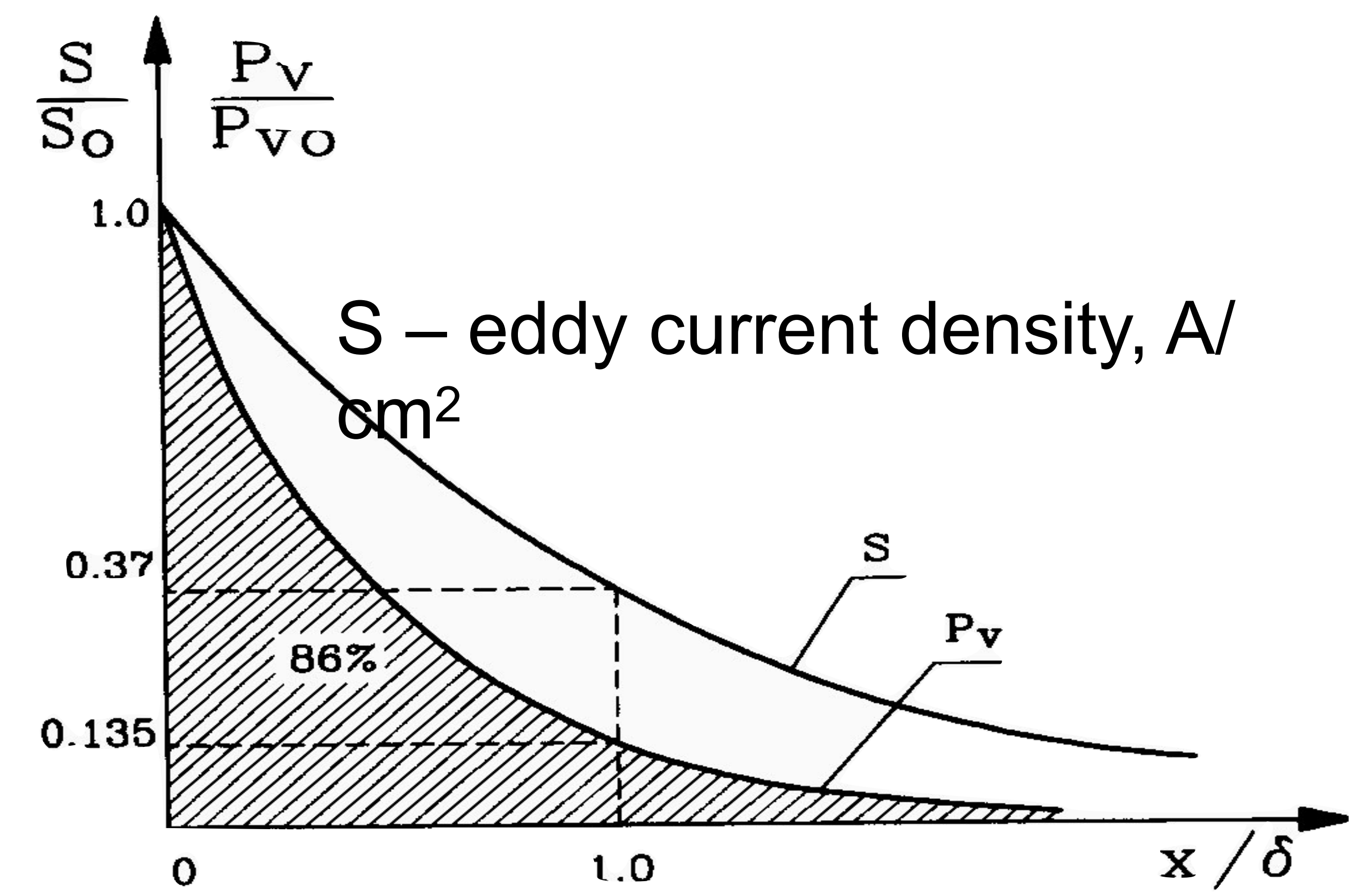
In a thick flat body the density of an eddy current drops from the surface exponentially and at the depth δ current density is only 37% of its value on the surface.

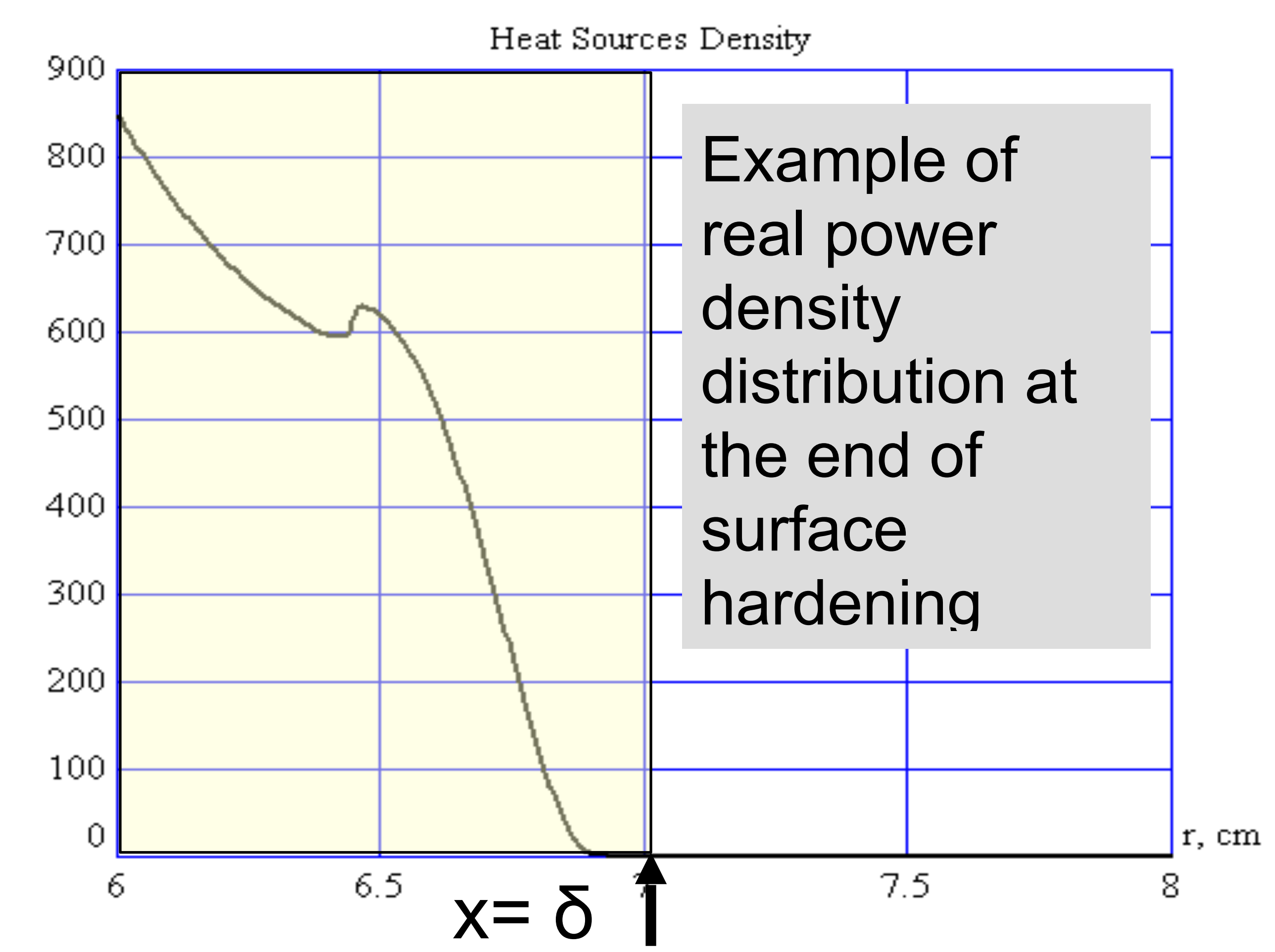
Power density drops as current density square and at δ it is only 13.5% of its value on the surface.

It allows us to say that **ALMOST** all power is generated inside of reference depth (skin layer).

If body thickness or radius are much bigger than δ we can say that skin effect is well pronounced and consider the body as flat.

In real cases of heating magnetic parts, power density distribution may be very different from exponential.





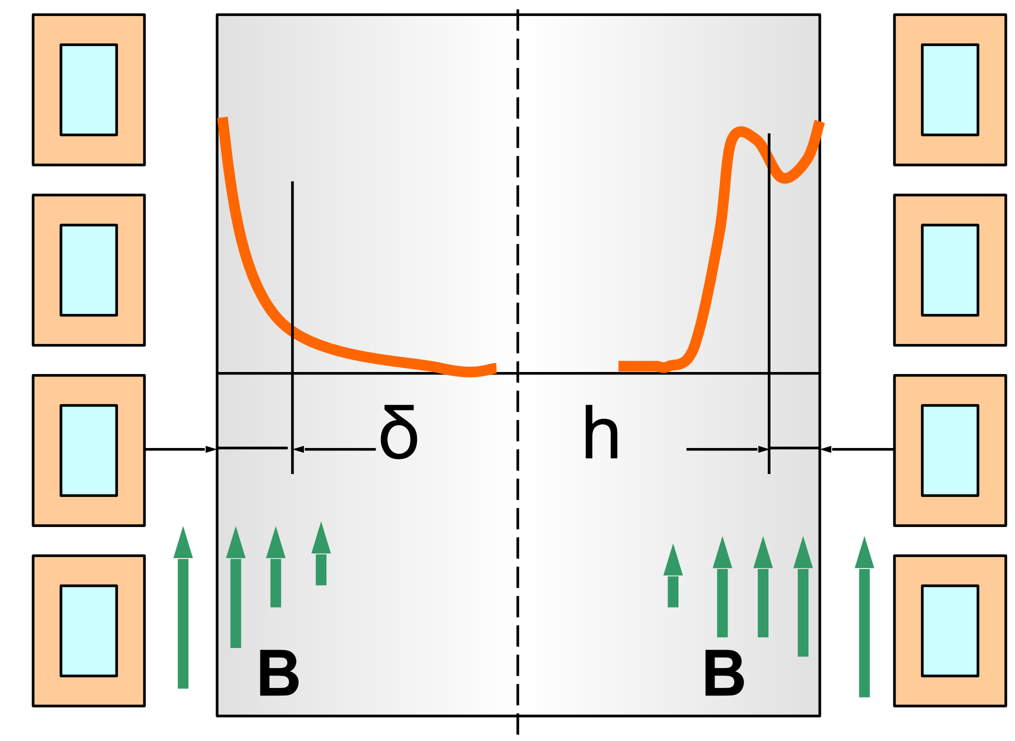
Examples of Power Distribution in Cylindrical Bodies

Though there are complicated analytical formulae for current and power distribution in cylinders, a modern way is to use computer simulation.

Power density (red lines) and flux density B (green arrows) distributions in a cylinder:

Left – non-magnetic part; δ – reference depth

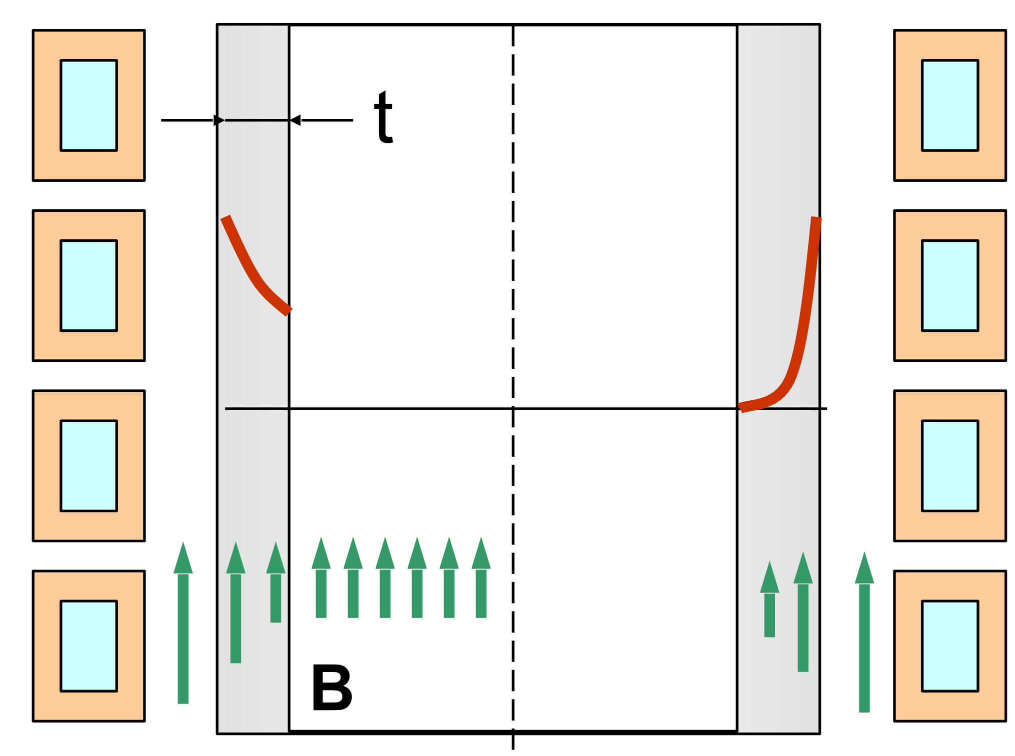
Right – magnetic steel at the end of surface hardening when the outer layer lost magnetic properties; h - austenitized layer that will be hardened after quenching.



Power density and B distribution in a tube:

Left – case of low frequency (wall thickness t is much less than reference depth δ). Magnetic field penetrates inside the tube.

Right – case of high frequency (wall is thicker than reference depth). Distribution is the same as in solid cylinder.



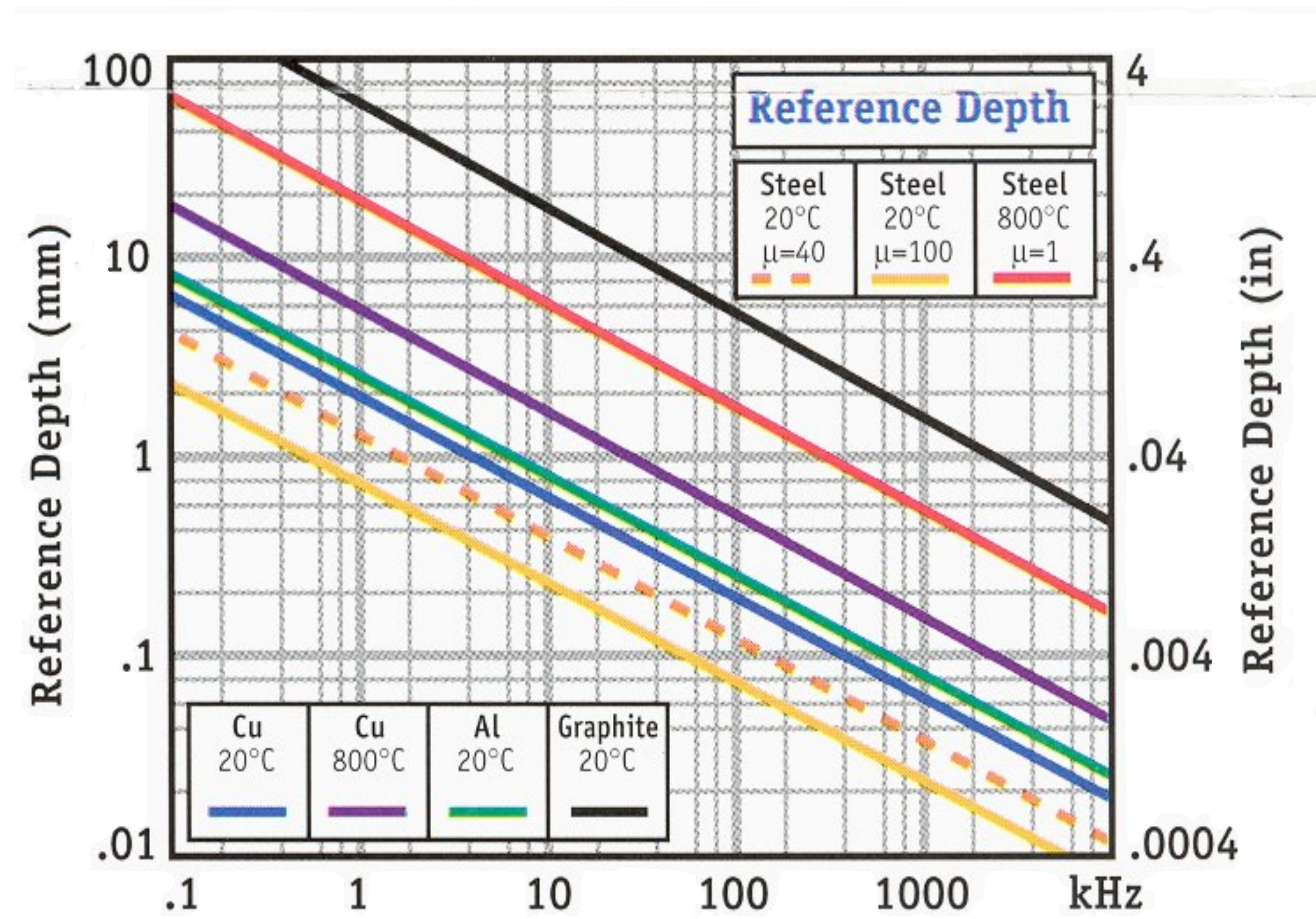
B – magnetic field density

Reference Depth for Different Materials and Frequencies

Reference depth is a unit of length that may be used for evaluation of electromagnetic processes in conductive body (coil copper, heated part, structural components etc.).

For through (mass) heating, one needs to compare part diameter and δ. If diameter of the body is smaller than reference depth, power absorption is poor and heating efficiency is low (the body is "transparent" to magnetic field).

For surface hardening we need to compare desired case depth and δ to evaluate if the frequency was selected properly.



It is a common practice to use logarithmic scales to cover wide ranges of frequency and delta variation

Power Absorbed by Workpiece

For parts of a simple shape (flat or cylindrical) placed in uniform magnetic field, absorbed power may be calculated analytically.

In many cases such as through heating of long parts this approach is quite accurate. It also gives a clear understanding of relations between power, frequency and part properties.

For real cases with non-uniform magnetic field and complicated part shape only computer simulation can provide accurate results.

$$Pw = \frac{\rho}{\delta} AKH^2$$

Pw – power absorbed by the workpiece

ρ – electrical resistivity of material

δ – reference depth

A – workpiece surface exposed to magnetic field

H – magnetic field strength (intensity) on the workpiece surface

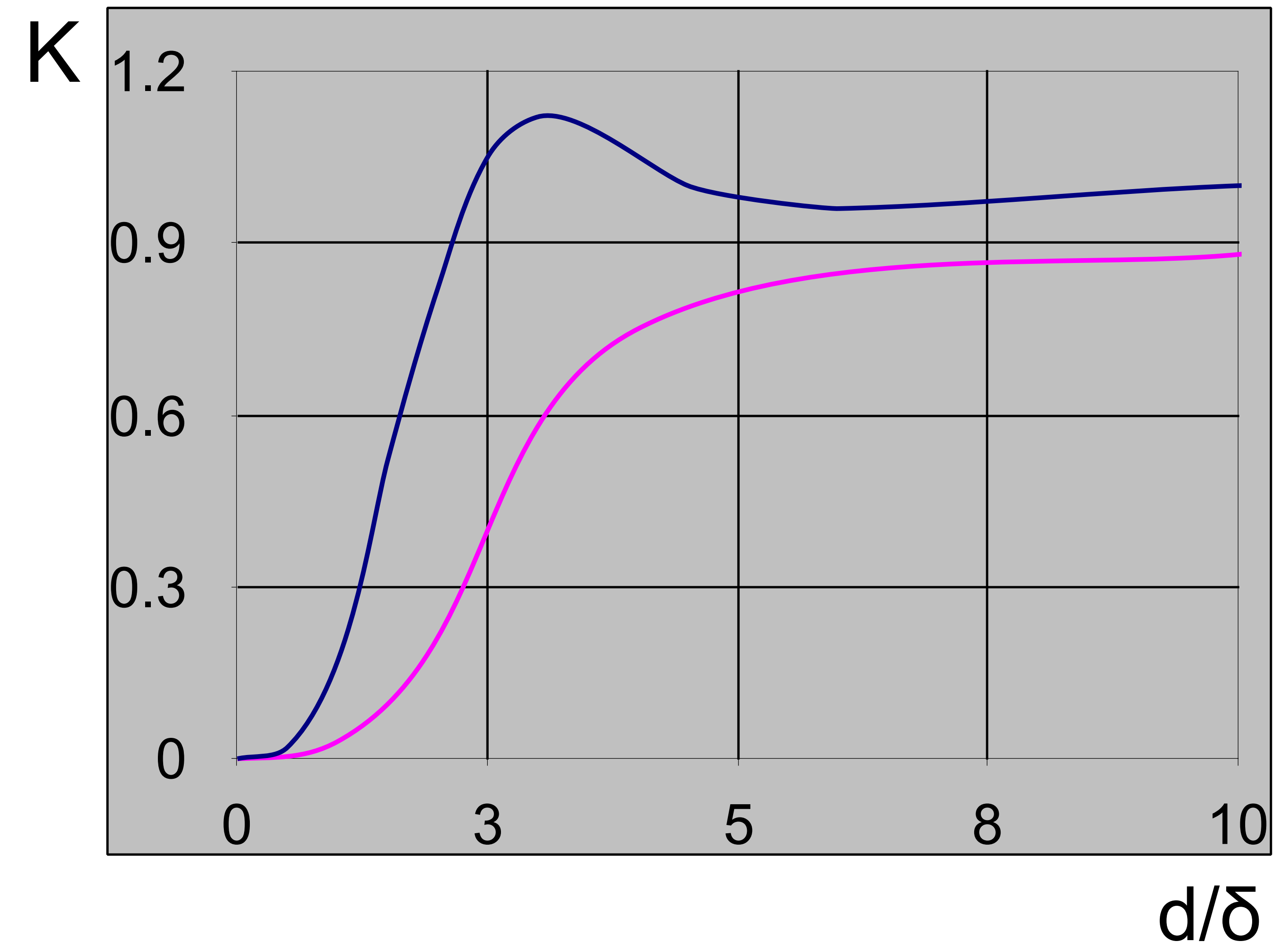
K – power transfer factor dependent on part geometry, material properties and frequency

Power Transfer Factor for Plate and Cylinder

When part thickness or diameter is small or frequency is low, electrical dimensions are small and K is small also. It is said that the body is transparent for magnetic field (at this frequency). Components of induction system or machine that must not be heated by induction (such as fixtures, fasteners etc.) must be transparent.

If size of body or frequency are big, K always tends to threshold value K = 1.

For cylinder there is no maximum of K and electrical efficiency grows with frequency. For plates there is a small maximum when its thickness equals to 3 reference depths (more exactly 3.14δ).



d – plate thickness or cylinder diameter

δ – reference depth

d/δ is "electrical dimension" of the body; it is proportional to root square of frequency

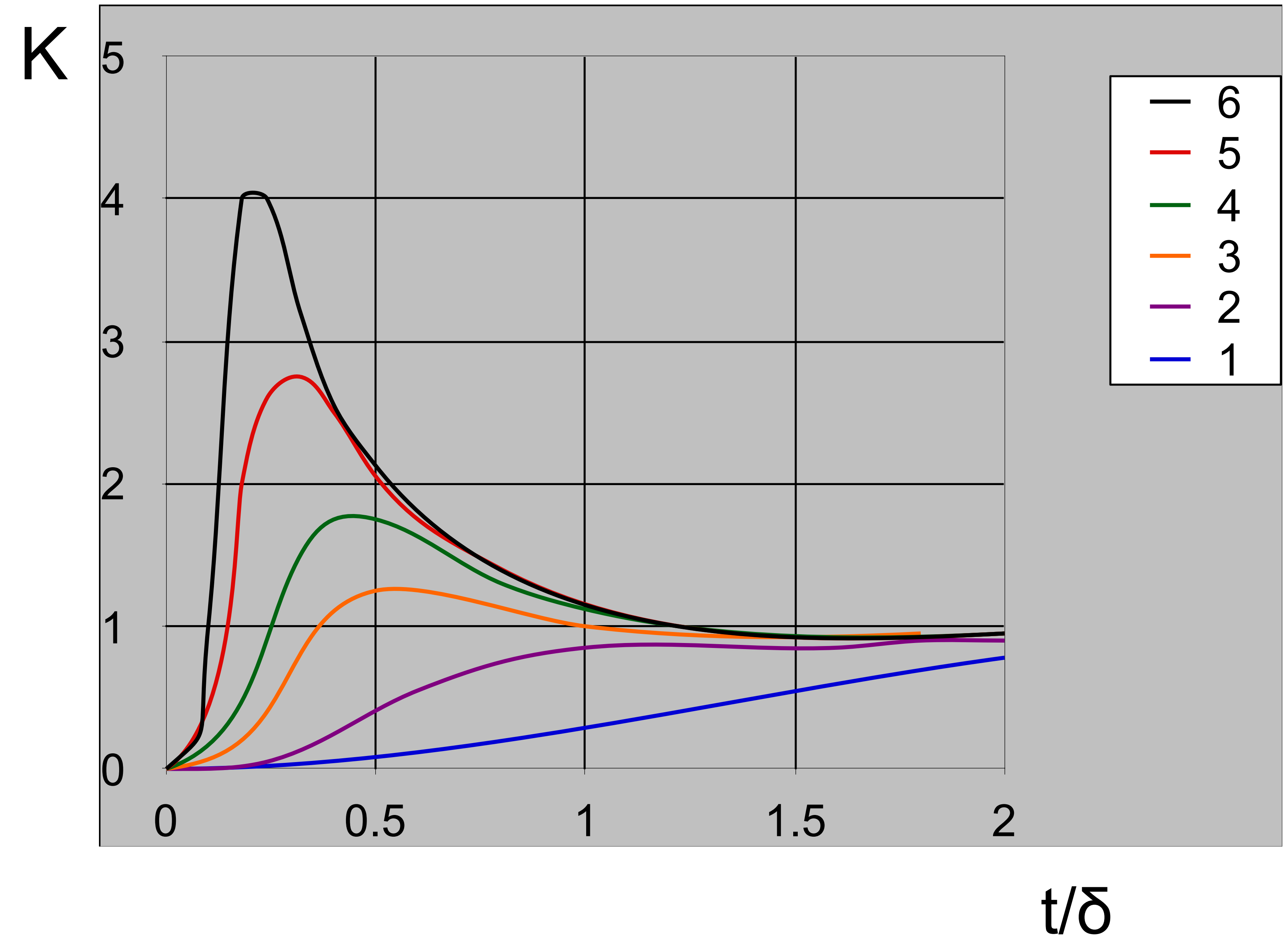
Power Transfer Factor for Tubes

For tubes there is a well-pronounced maximum of K. It is higher for thin-walled tubes (small ratio t/d).

It is desirable to select frequency that provides values of K close to maximum.

Electrical dimensions of tube may be described by a product of t/δ and d/δ. Maximum of the coil electrical efficiency corresponds to $td/\delta^2 = 3.5$.

Account of final lengths of the induction coil and heated tube gives slightly higher optimal frequency.



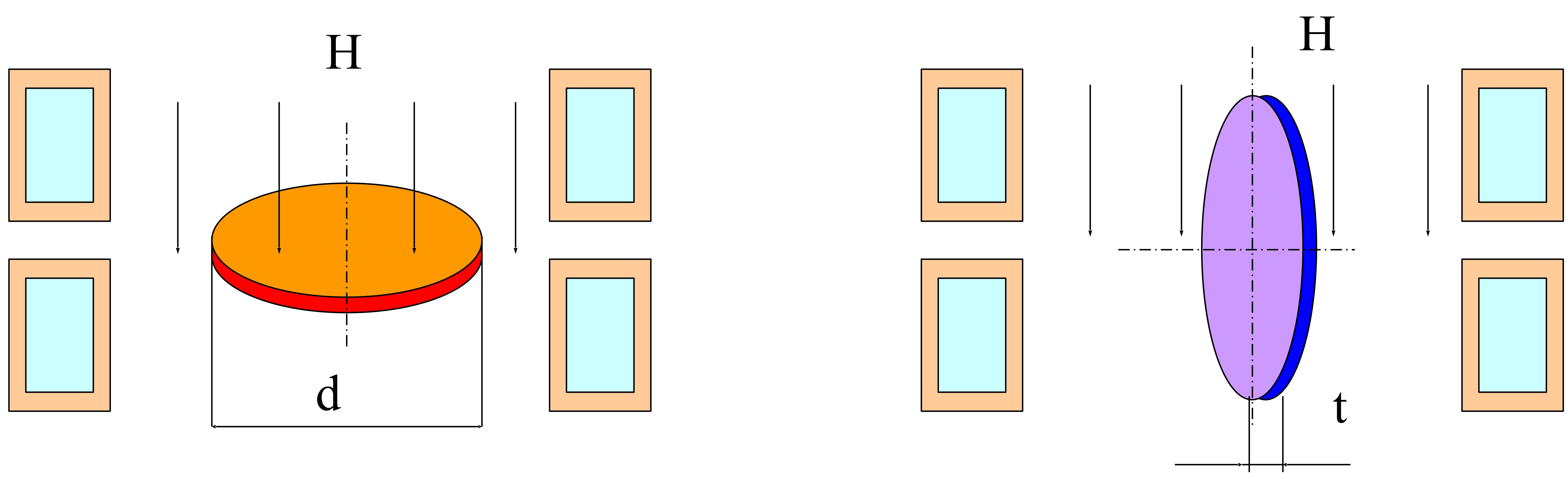
Power transfer coefficient for tubes
t – tube wall thickness
d – outer tube diameter

Curve	1	2	3	4	5	6
t/d	0.5	0.2	0.1	0.05	0.02	0.01

Thin or Thick Part ?

Power absorption depends also on the part orientation in magnetic field. Maximum absorption happens when the part surface is perpendicular to magnetic lines

H – magnetic field strength lines



"Transverse" Heating

Longitudinal Heating

d >> δ - Good Heating t < δ - Bad Heating

Electromagnetic Effects in Induction Systems

Complicated distributions of magnetic field, induced current and power density, which influence the resulting temperature distribution in the body, may be conveniently described by means of "Electromagnetic Effects":

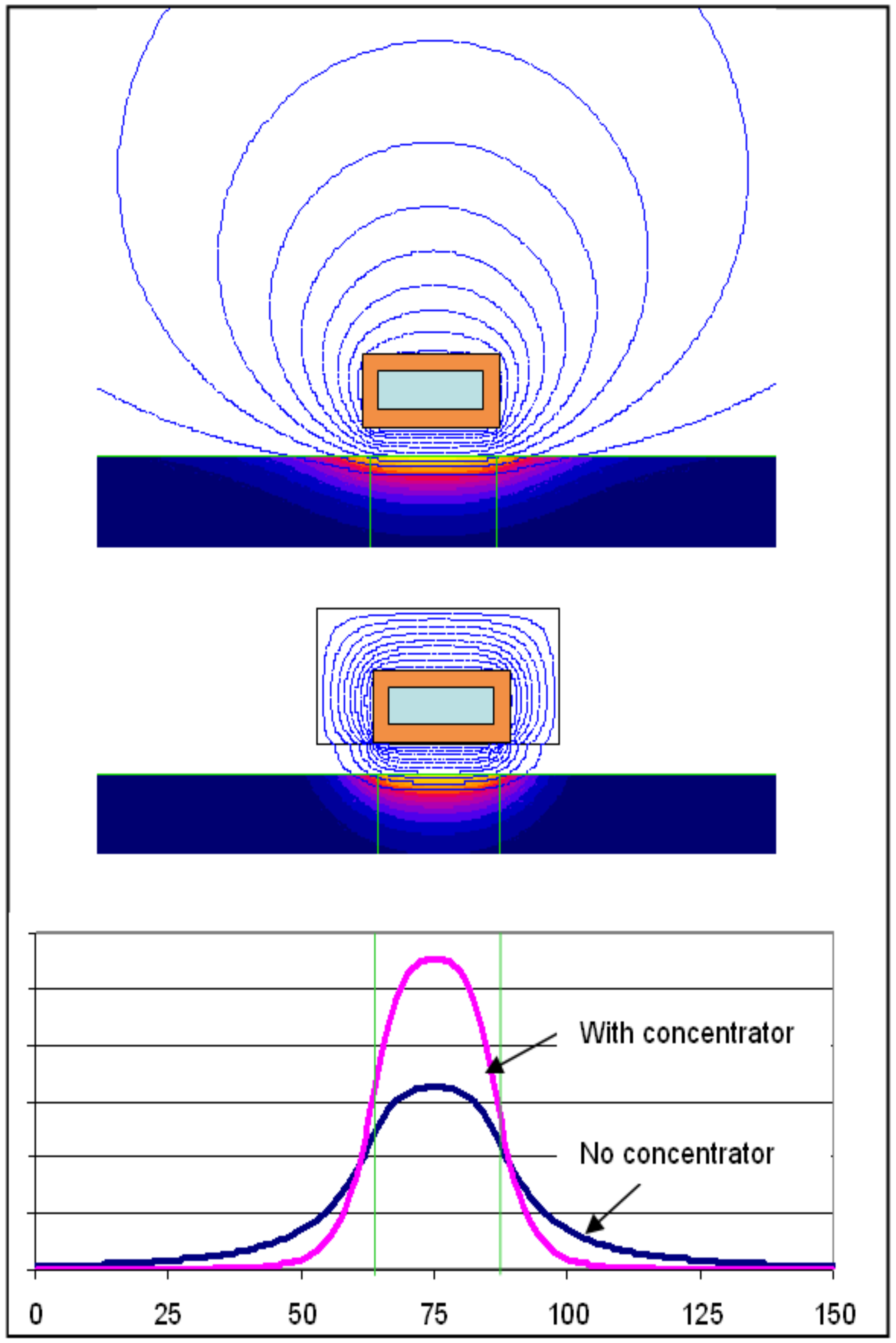
- Skin effect (previously described)
- Concentrator effect
- Proximity effect
- End effects
- Edge effect of slabs and strips

Concentrator Effect

Magnetic flux concentration is one of the types of flux control, which also includes shielding, deviation or other magnetic field modification.

Application of C-shaped concentrator to coil tubing results in dramatic reduction (elimination) of external magnetic field, in higher power in the part under the coil face (for the same coil current) and in reduction of power outside of the coil face zone.

On the other side the C-shaped concentrator pushes the coil current to its face reducing the cross-section of current flow. Losses in the coil grow. When concentrator is properly applied its benefits overcome this effect.

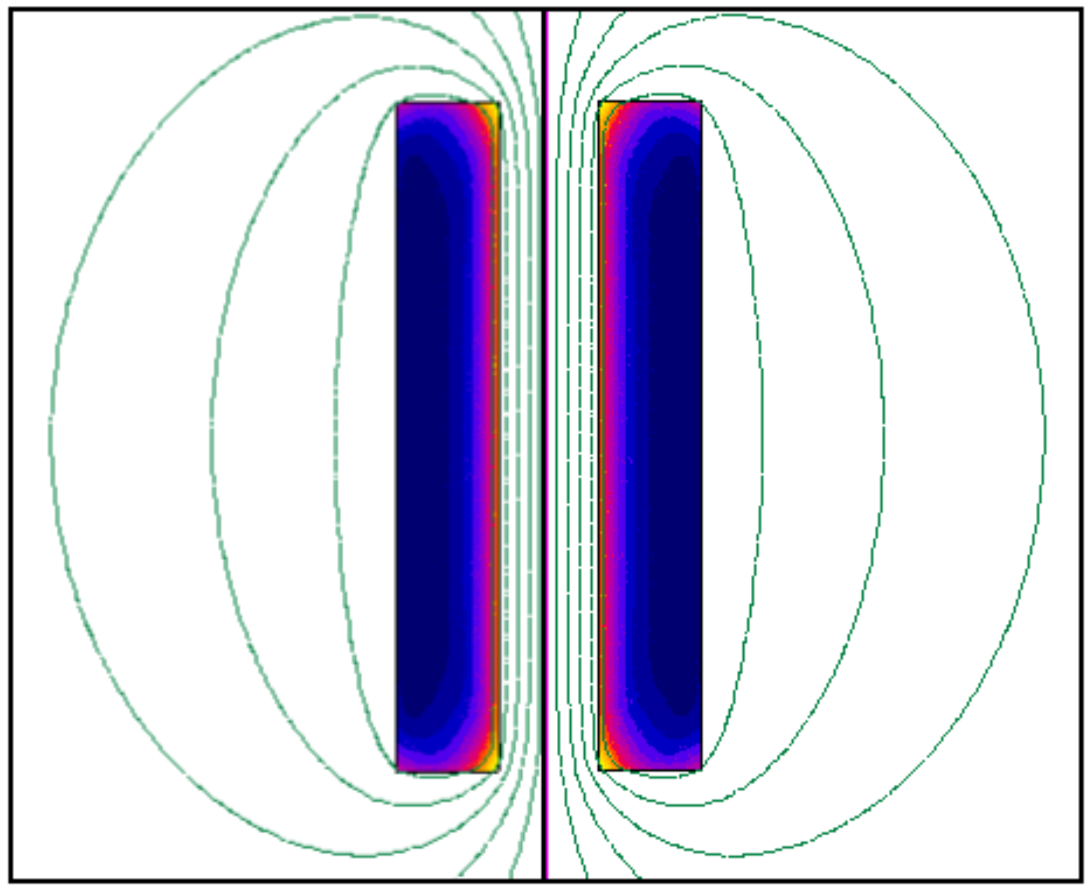


Power distribution on the part surface

Proximity Effect in "Coil - Flat Body" System

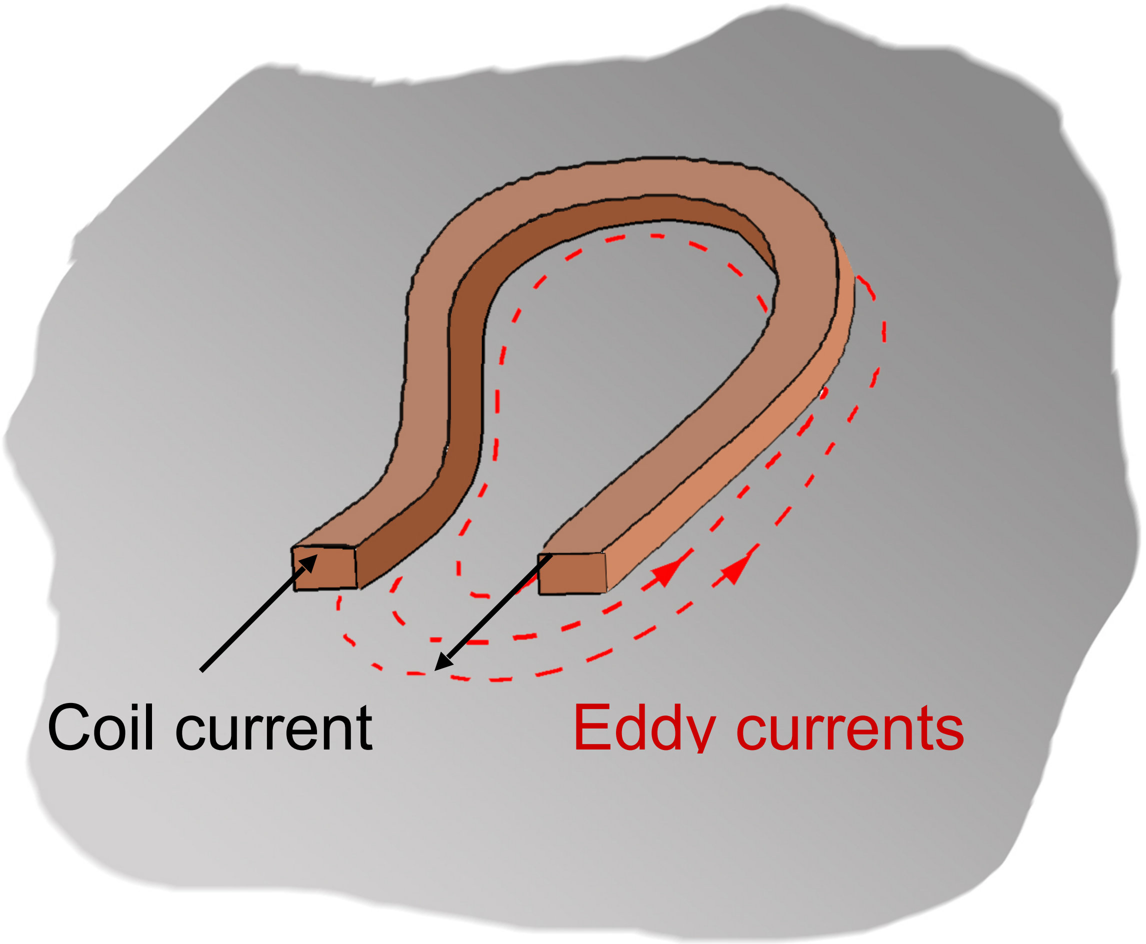
Alternating currents of opposite directions tend to flow in the way closest to each other. This phenomenon is called Proximity Effect. Proximity effect is stronger at high frequency and small gap.

In a two buss system, currents of opposite direction flow mainly on the surfaces facing one to another (see color map of current density and magnetic field lines simulated with Flux 2D program).



Induction coil located above the part surface generates eddy currents that tend to flow just under the coil face. Coil geometry controls resulting heat pattern.

Concentrators strongly increase proximity effect and additionally help to control heat pattern.

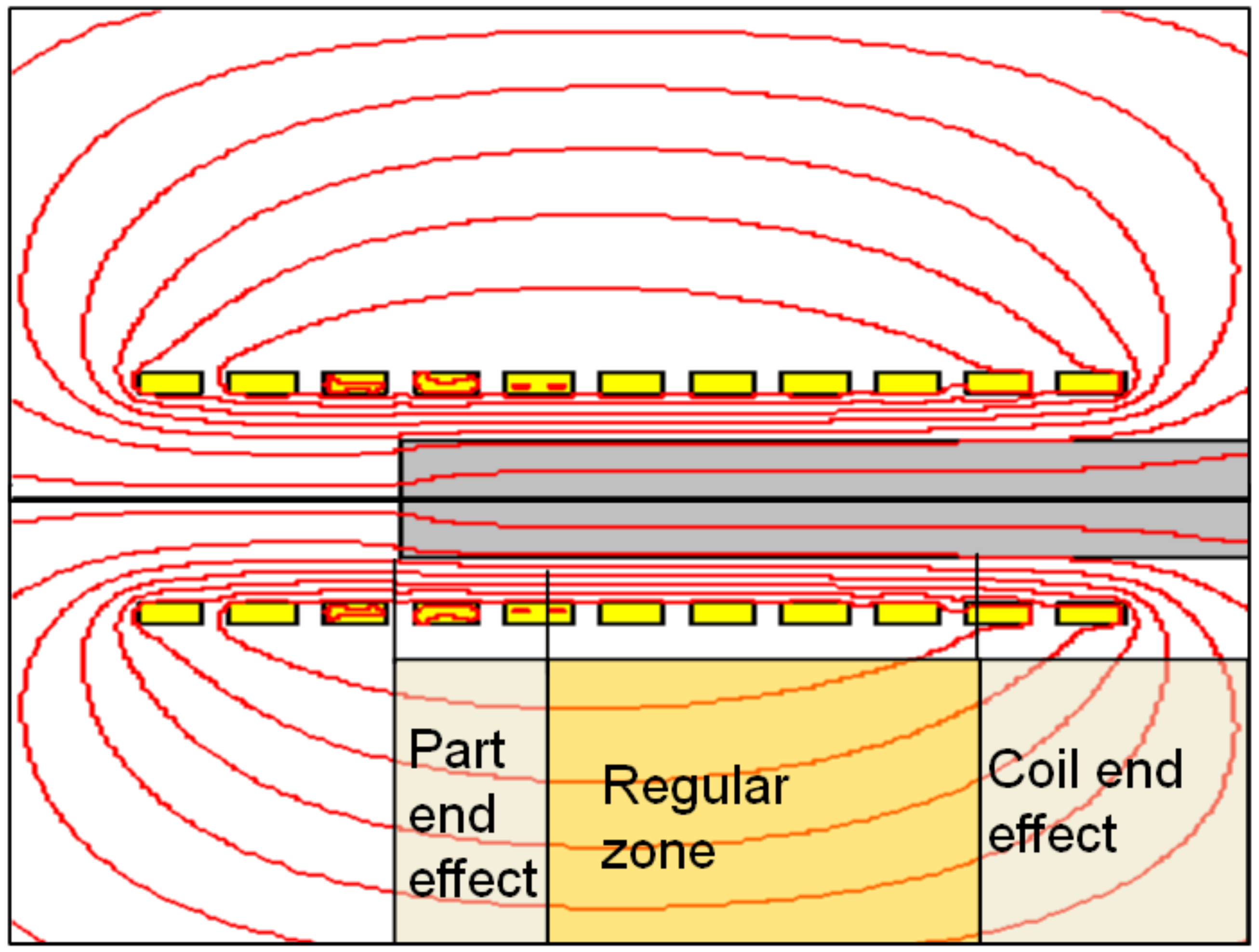


End Effects in Cylindrical Induction System (non-magnetic body)

Due to end effect of the coil power in the workpiece drops gradually near the coil end. A flux concentrator can make power distribution more close to rectangular improving temperature uniformity in required length.

End effect of the part is caused by magnetic field distortion near the part end. It may be positive (higher power to the end) or negative (lower power to the end). Negative effect is typical for magnetic parts at low frequency, for example in tempering process.

Positive end effect of the workpiece may be compensated by coil end effect, i.e. by proper selection of part position inside the coil. Negative end effect may be compensated by coil design and/or application of concentrators.



Flux 2D program

Magnetic field line pattern for the coil with non-magnetic workpiece (top).

Power distribution (p) in the length (z) of the part for magnetic and non-magnetic materials (bottom).

a – workpiece End Effect zone

b – coil End Effect zone

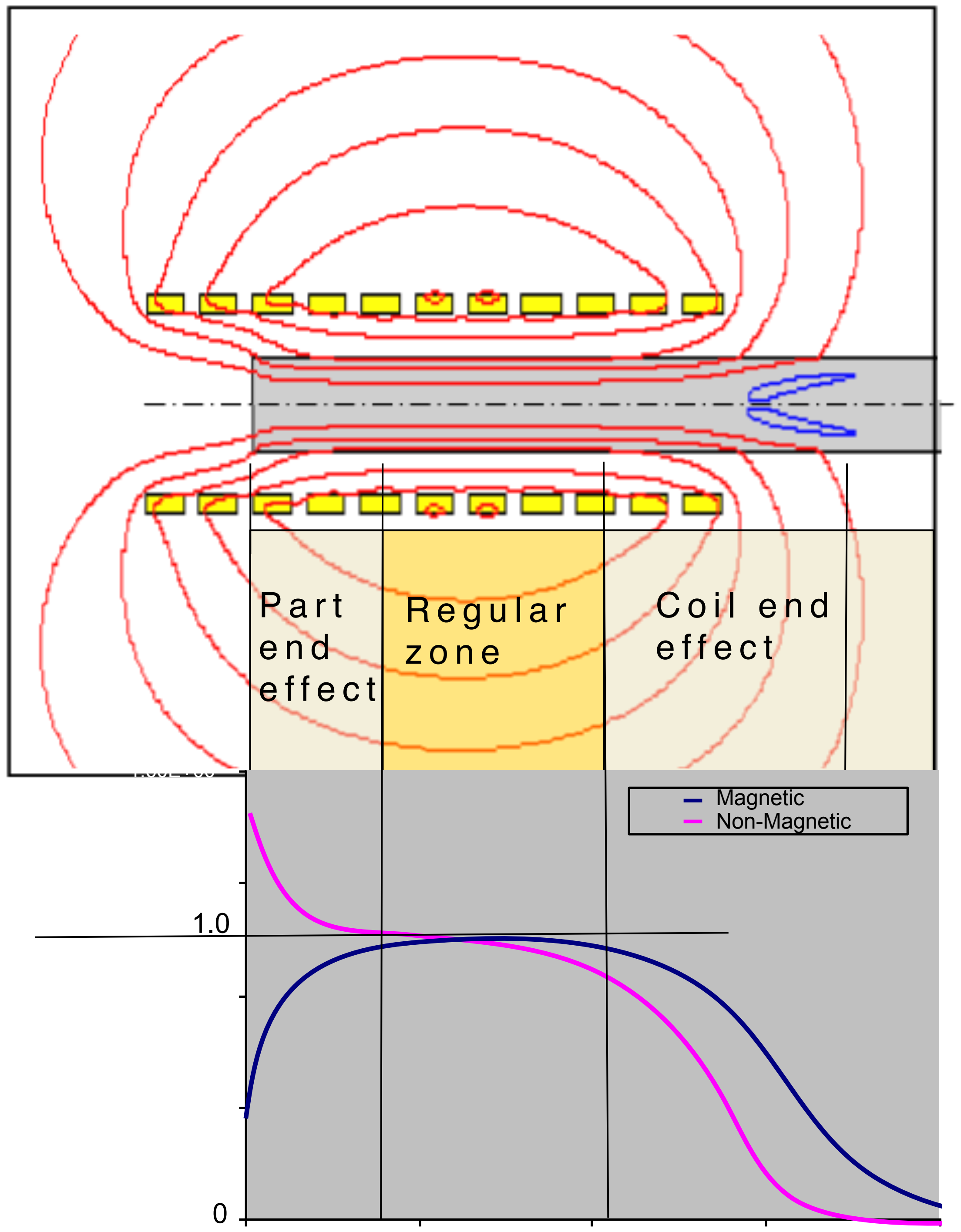
End Effects in Cylindrical Induction System (magnetic body)

Magnetic field lines of the coil with magnetic workpiece at low frequency as generated by Flux 2D program. Half of a cylindrical system is shown.

Part of magnetic lines leaves the workpiece before the end resulting in less end zone power (**negative end effect**) and lower temperature.

A length of underheated end zone is approximately one diameter.

Distribution of power and temperature along the part may change in the process of heating. For example, temperature of the part end may be lower than in a regular zone when the part is magnetic. Above Curie temperature the part becomes non-magnetic and the end zone may quickly reach or even exceed the regular zone temperature.



Power density distribution due to the coil and part end effects:

magnetic at 60 Hz
non-magnetic at 3000Hz

See "End Effects Influence on Temperature Distribution" Video

End and Edge Effects in Induction Heating of Slabs and Strips

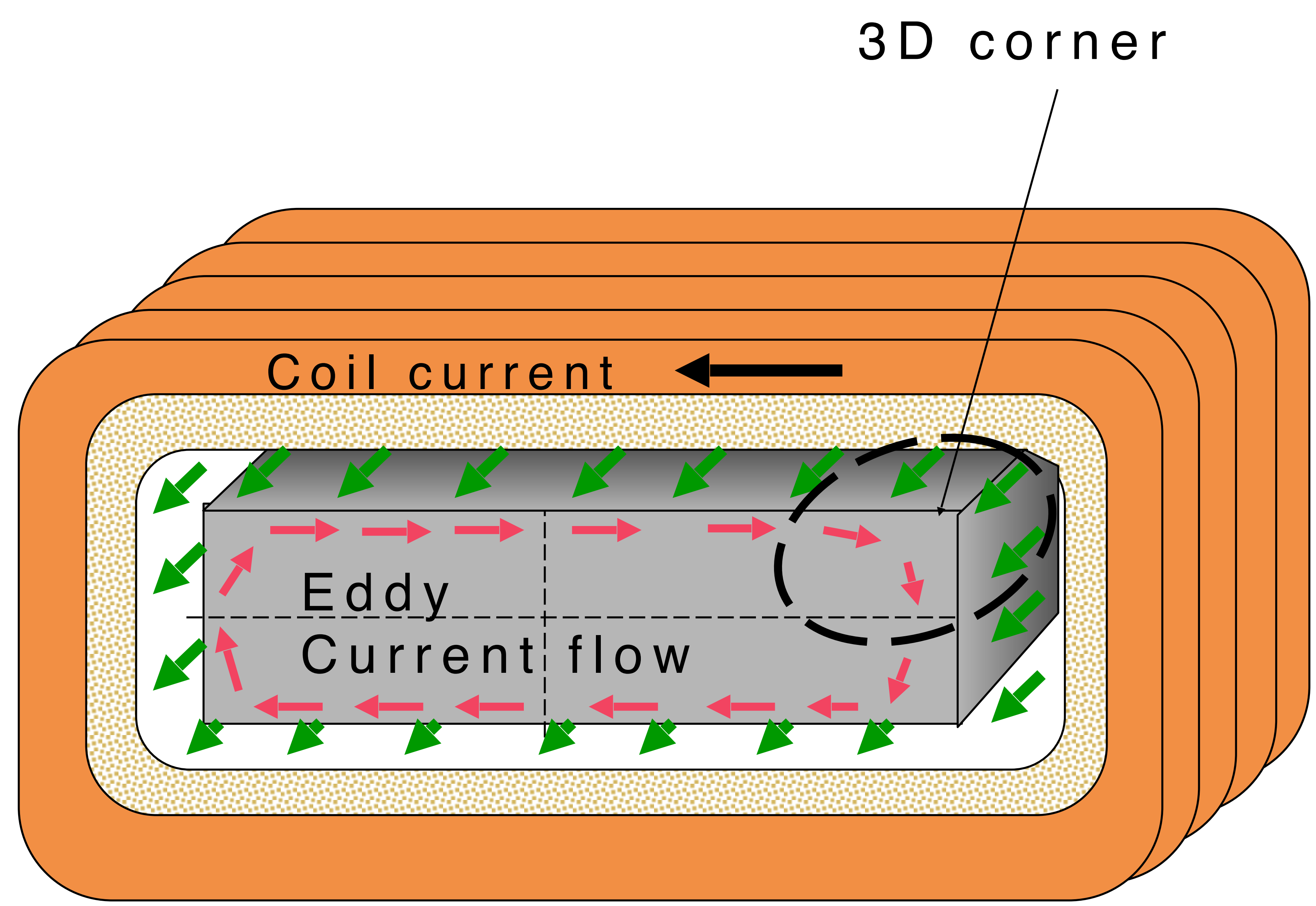
Heating of rectangular bodies (slabs, strips, foils) is essentially a 3D problem.

If slab thickness is significantly less than width and length, it is possible to consider central zone as a 1D area.

In side areas eddy currents bend 180 degrees forming zones of Edge Effect.

Near the ends of slab there is distortion of magnetic field, which tends to “cut” the corner. This is a zone of End Effect similar of End Effect zone of cylinder.

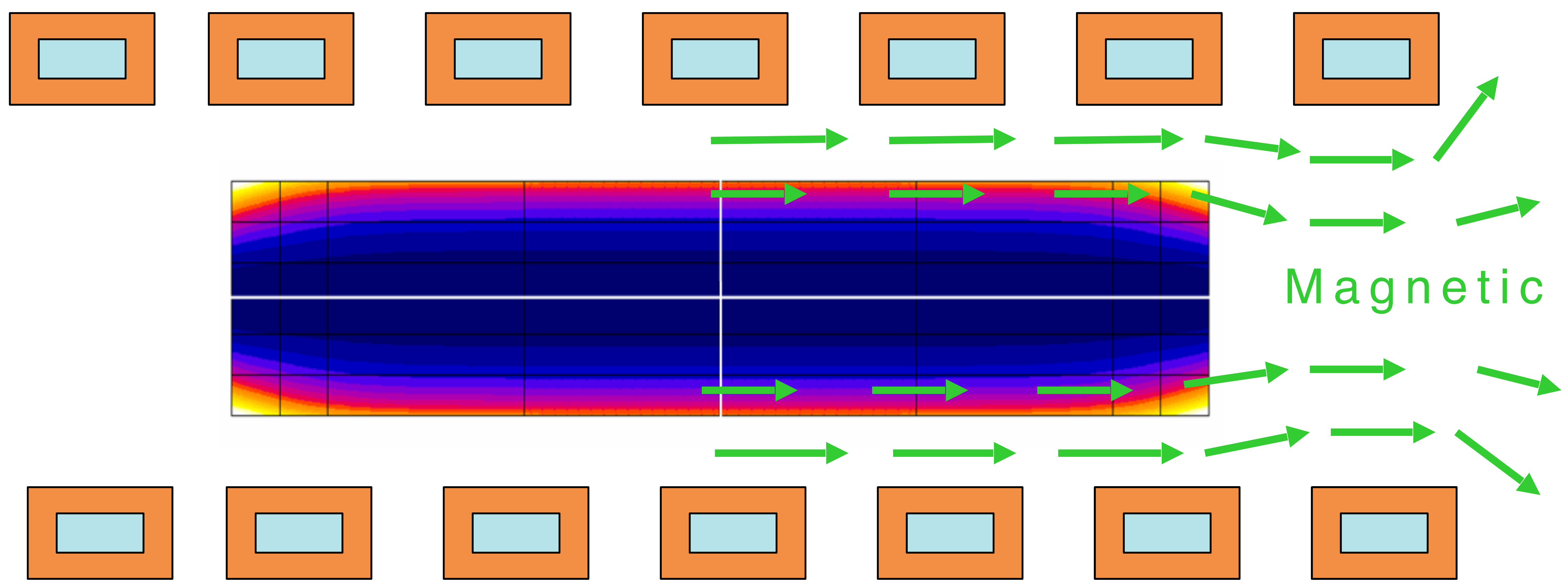
Area of 3D corner is a special zone where End and Edge Effects interfere.



Slab heating in multi-turn oval inductor

Power Density Map Demonstrating End Effects in Non-Magnetic Slab

Stainless steel slab (map in 1/4 of longitudinal section is shown); frequency 9.5 kHz
Flux 3D simulation program



End effect in non-magnetic body is always positive, i.e. there is extra power near the body end.

Power and temperature distribution in slab length may be controlled by its position inside the coil or by magnetic flux controller.

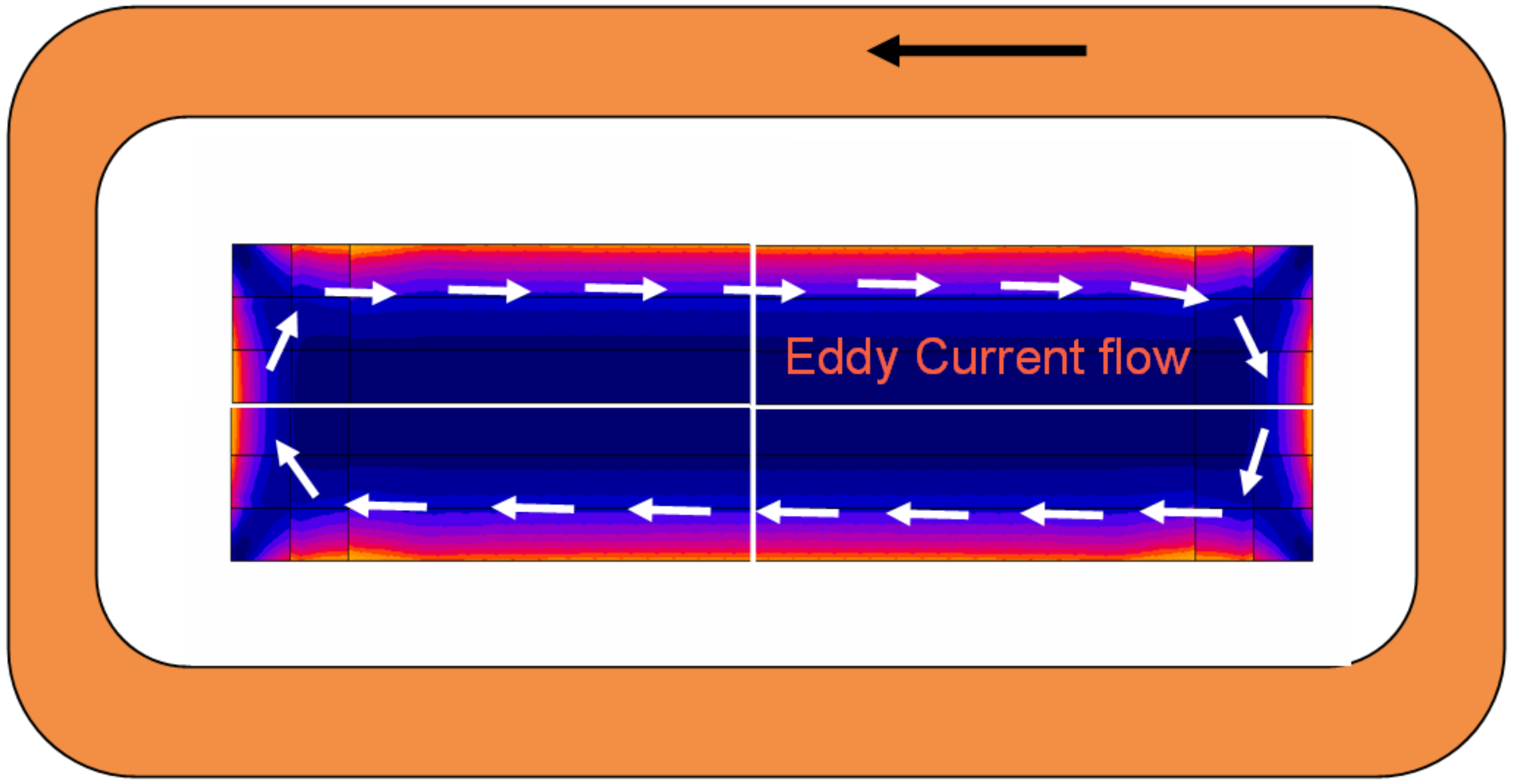
Power Density Map Demonstrating Edge Effects in Magnetic & Non-Magnetic Slabs

Edge effect in rectangular body may result in underheating or overheating of the slab edge zone.

Underheating happens when slab thickness is less then 3 Reference Depths.

Overheating – when thickness is more than 3 Reference Depths, which is typical for magnetic slabs.

Thus frequency selection is critical for uniform heating of slab in its width.



Stainless steel slab (color map in 1/4 of cross-section is shown). Frequency 9.5 kHz

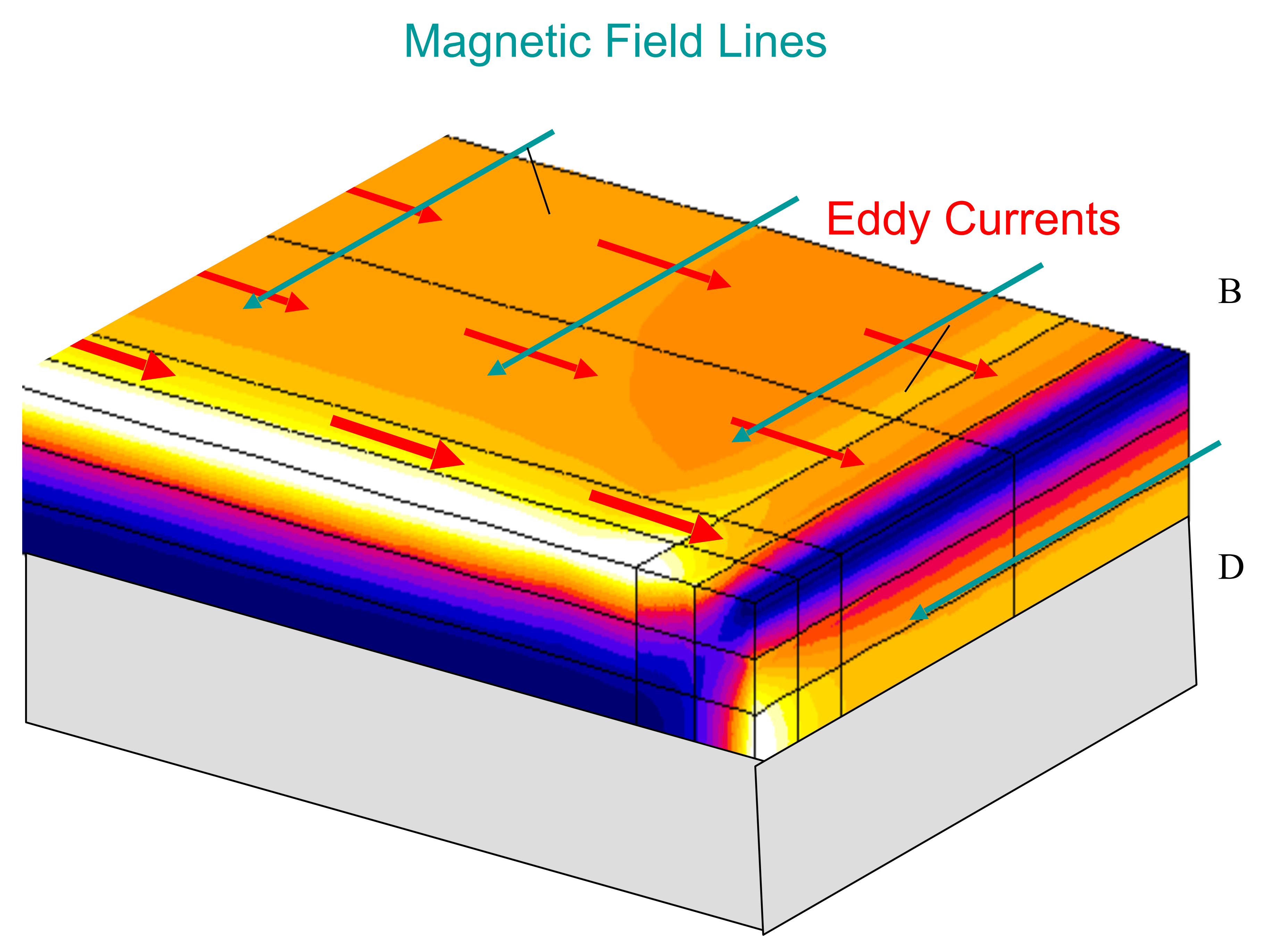
Flux 3D simulation program

Power Density Map in Non-Magnetic Slab (3D Corner Zone)

Combination of End and Edge effects near the 3D corner of non-magnetic steel slab.

Approximately 1/8 of the whole slab is shown.

3D effects near the corner are complicated.



Flux 3D simulation program

Questions and Answers

- What are the mechanisms of power absorption in induction heating?

  Eddy Current and Hysteresis
- Eddy Current heating occurs in what type of materials?

  Conductive
- Hysteresis heating occurs in what type of materials?

  Magnetic
- Hysteresis provides main part of heating power in magnetic materials composed of?

  Individual particles
- What are the 3 closed loops of any induction device?

  Coil Current, Magnetic Flux, Eddy Current
- Coil active Power can be described as the power being?

  Absorbed by the coil from supplying circuitry
- Coil reactive Power can be described as the power being?

  Reflected by the coil
- The unit of length used for evaluation of an electromagnetic process in a conductive body is?

  Reference (Penetration) Depth
- The 5 main electromagnetic effects in induction systems are?

  Skin, Concentrator, Proximity, End and Edge Effects.

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