FLUXTROL®

Advanced Induction Materials and Technology

Online Induction Heating Course

5. Basics of Magnetic Flux Control in Induction Systems

by. Dr. Valentin Nemkov

FLUXTROL®

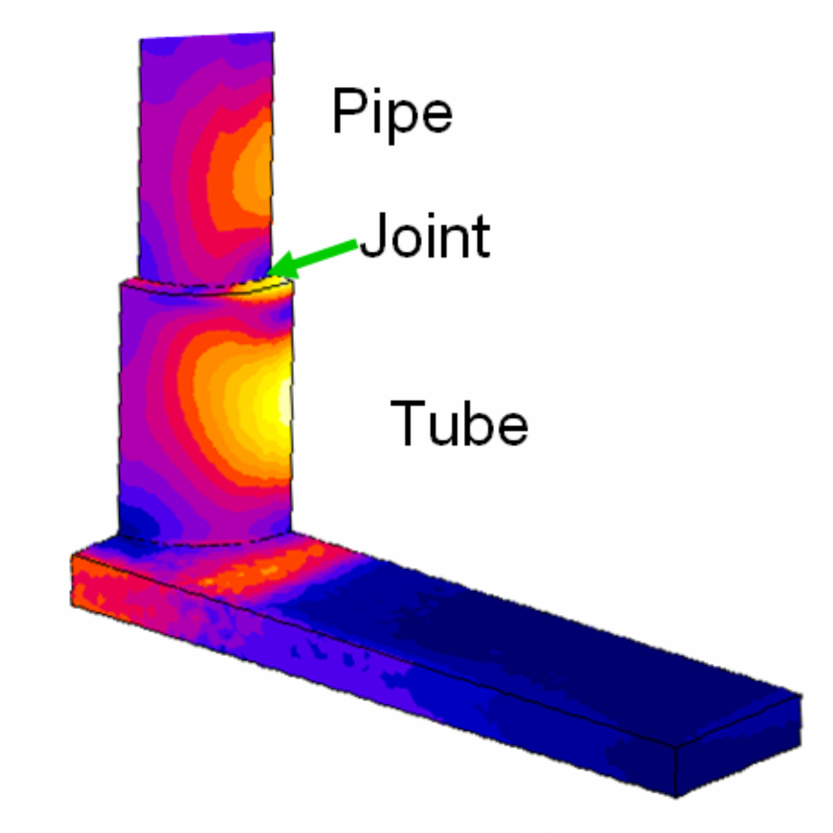
What is Magnetic Flux Control?

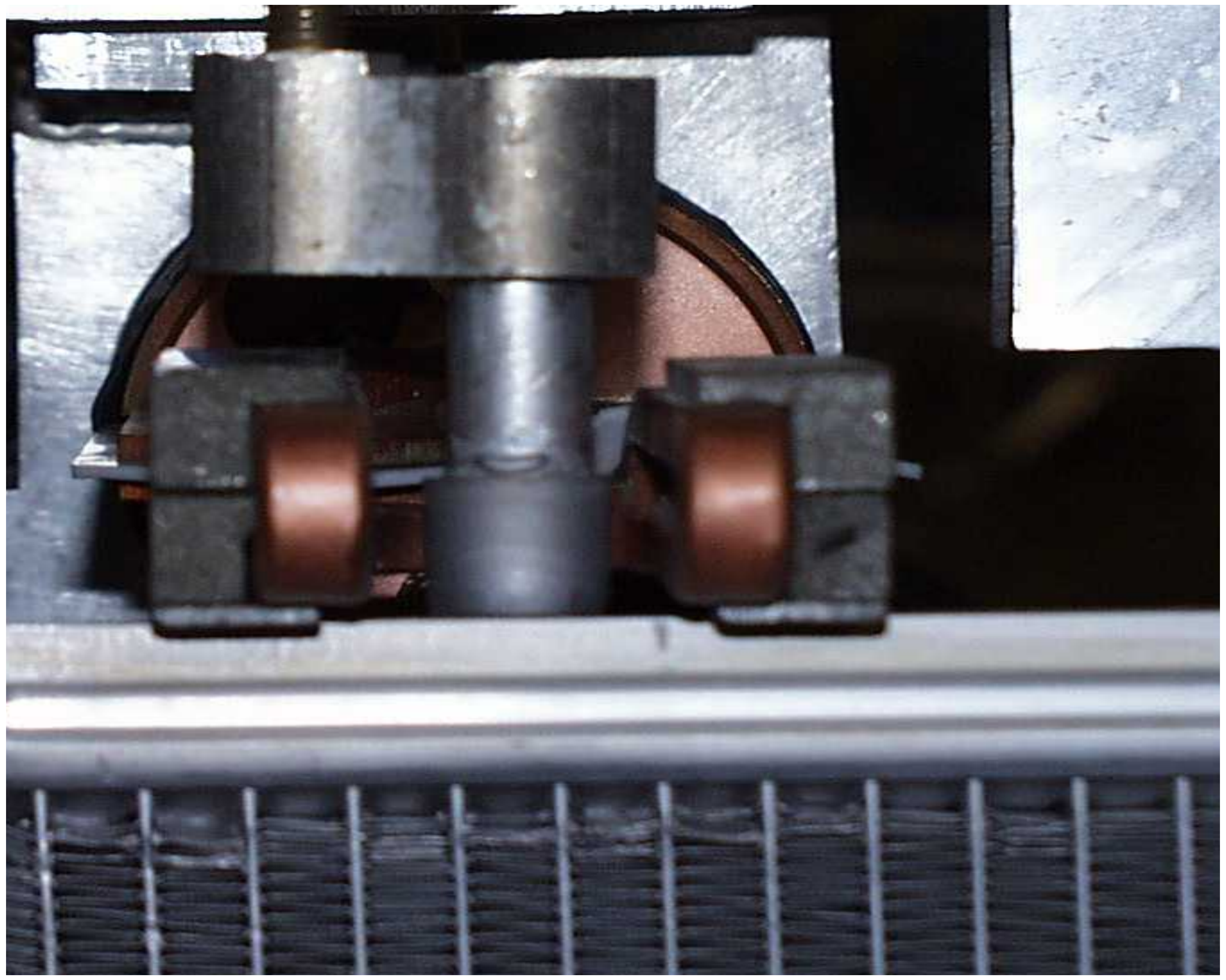
- In this course magnetic flux control is a generic term for modification of induction coil magnetic flux by means of installation of magnetic templates (magnetic flux controllers). Magnetic flux control due to application of non-magnetic bodies (Faraday rings or flux robbers) is not considered here.
- Magnetic controllers may significantly change magnetic field pattern and coil parameters; their application must be considered as a part of the whole induction system design.
- Because Controllers play different roles (magnetic flux concentration, shielding, distribution) they are called also Concentrators, Cores or Shields depending on application.
- In many cases controllers fulfill several functions simultaneously.

Combination of Several Effects of Magnetic Flux Controllers

Optimal power distribution between the system components.

Flux 3D program





Part: Aluminum heat exchanger
Operation: Tube-to-Pipe brazing
Concentrator effects:

- Optimal power distribution between Tube and Pipe
- Controlled shielding of the head of heat exchanger
- Total efficiency improvement resulting in heating time reduction from 25 to 15 sec
- Variation of Fluxtrol concentrator allows the use of the same coil copper for brazing a family of products (**see more details in Case Stories**)

Possible Improvements due to Application of Magnetic Flux Controllers

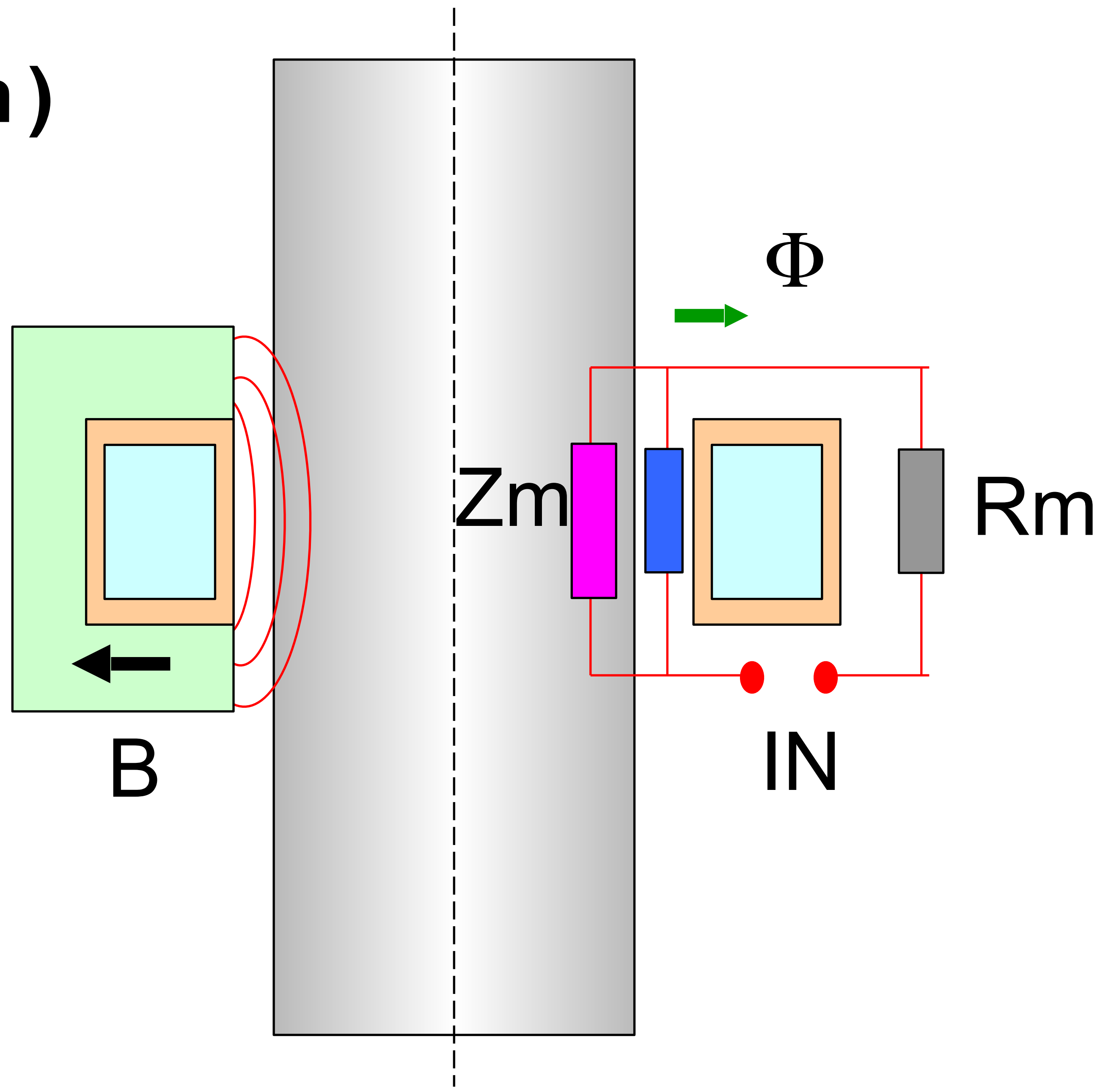
- Precise heat pattern control
- Power saving or production rate increase due to improvement of induction coil efficiency and better utilization of power in the workpiece
- Lower current demand for the same power
- Extended coil lifetime
- Improvement in power supply performance due to higher coil power factor and lower current demand
- Shielding of part or machine components from unintended heating
- Reduction or elimination of external magnetic fields (safety and electromagnetic compatibility issues)

Effects of Magnetic Flux Controllers on O.D. Coils

The role of magnetic flux controllers and their effects may be explained and evaluated by composition of magnetic flux circuit similar to electric current circuit.

$$\Phi = IN / (Zm + Rm)$$

- Φ (phi) – Magnetic Flux causing heating
- IN – Ampere turns of the coil (driving force of magnetic flux)
- Zm – Magnetic resistance (Reluctance) of the “active zone”
- Rm – Magnetic resistance for magnetic flux on **return path**
- B – Magnetic Flux Density (Induction). It describes magnetic loading of controller material.



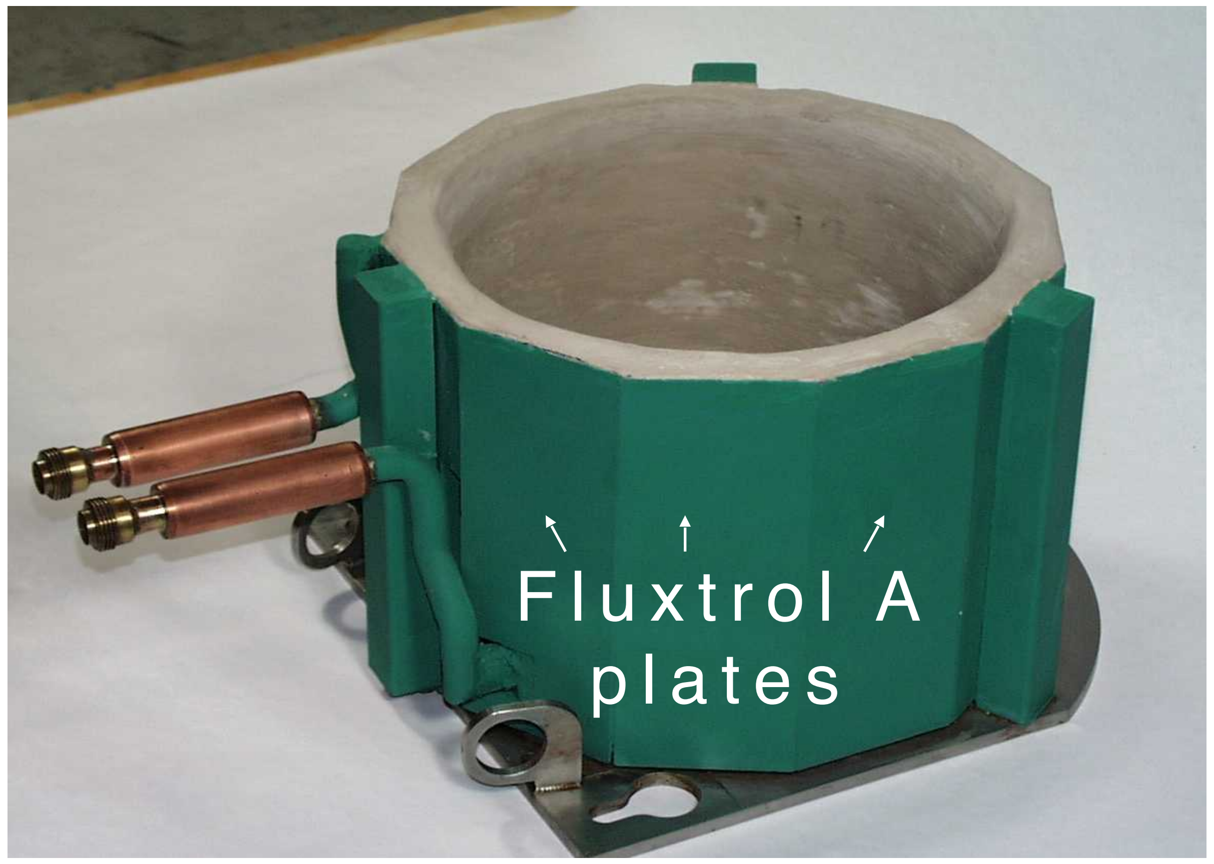
Applying controller we reduce Rm and therefore increase magnetic flux with the same coil current or reduce current demand for the same flux and heating power. Effect of controller is higher when Rm is high compared to Zm.

Improvements Expected for O.D. Coils

- Improved Heat Pattern Control /Ability to Heat Difficult Areas (axle fillet, etc.)
- Better Utilization of Power in Workpiece for short static coil (energy savings up to 30%)
- Lower Coil Current and therefore reduced losses in supplying circuitry – transformer, capacitors, busswork
- Shielding of part and machine components from unintended heating
- For long OD coils – small or no coil parameter improvement. However, in some cases local temperature control and shielding is required – see coil on slide 4.
- Heat treating of some difficult parts can not be achieved without application of flux controller

Melting Inductor for Glove Box Environment

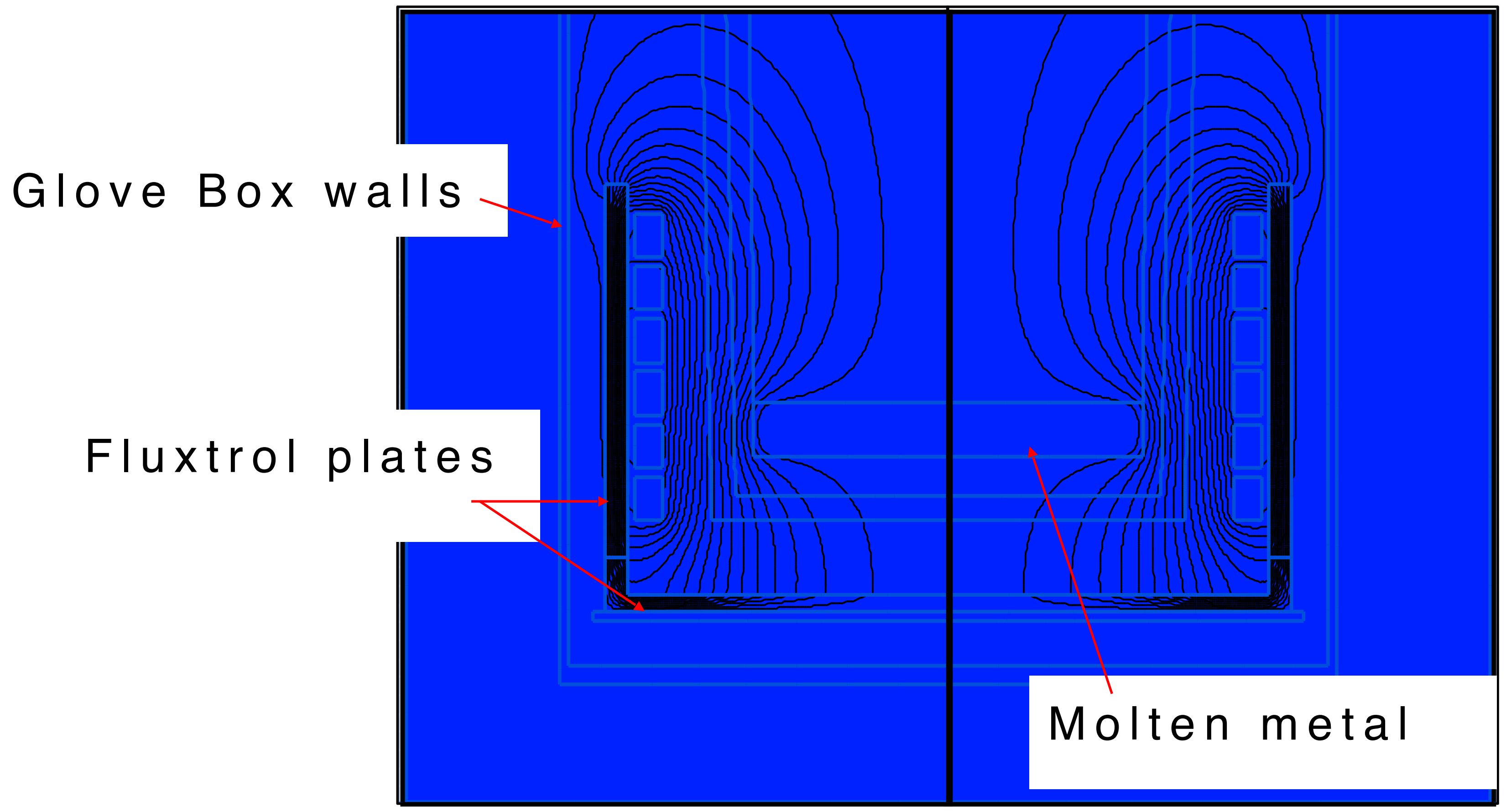
Induction coil for melting of radioactive materials in protective atmosphere



Example of shielding effect and efficiency improvement

Fluxtrol A shields on the side and bottom coil surfaces allowed to:

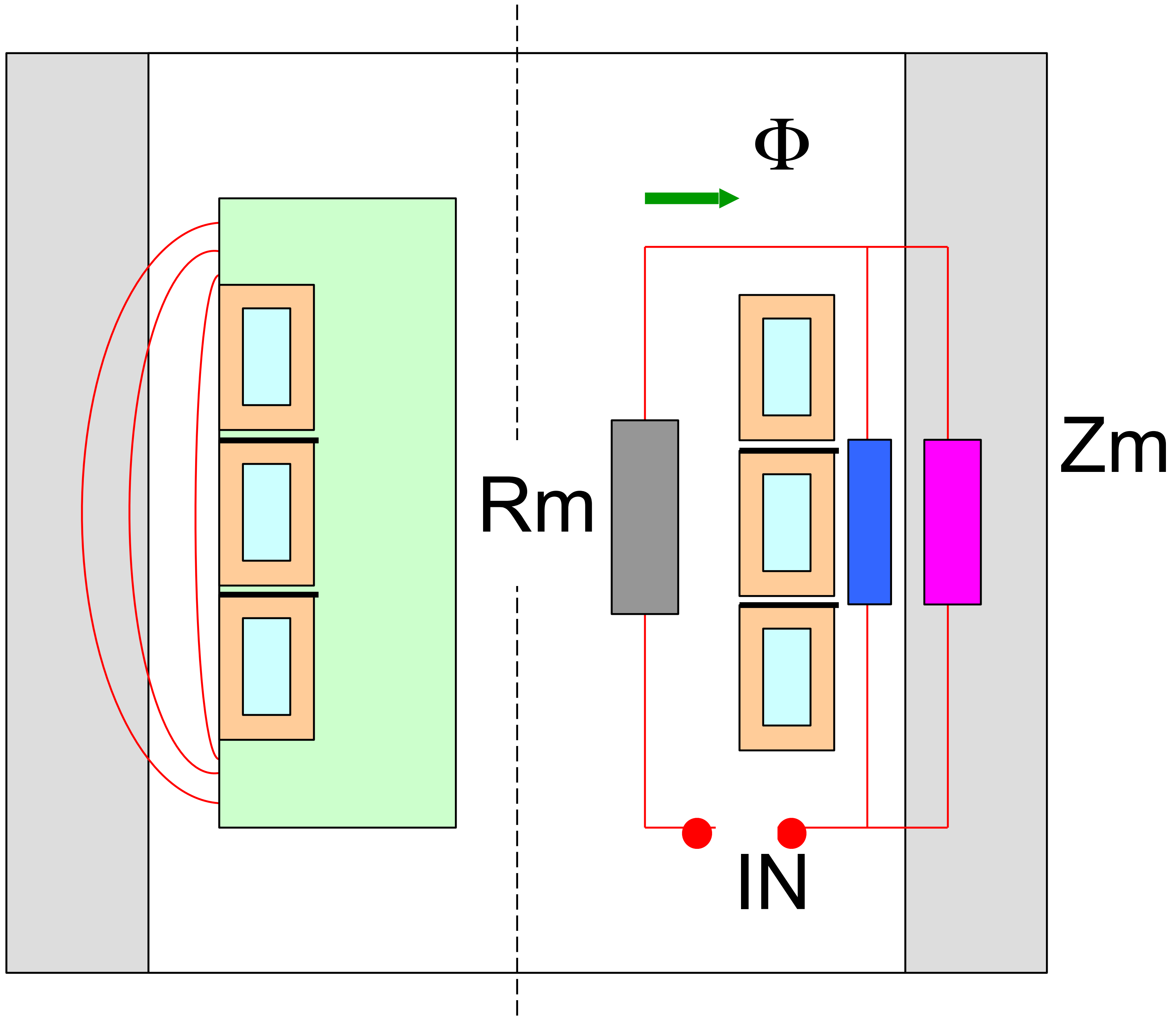
- Strongly reduce losses in the chamber walls and bottom plate
- Increase the furnace volume in the same chamber
- Increase coil efficiency from 23 to 63% due to reduced losses in chamber walls, bottom plate and in the coil



Magnetic field lines and color map of power density in a shielded coil with molten metal

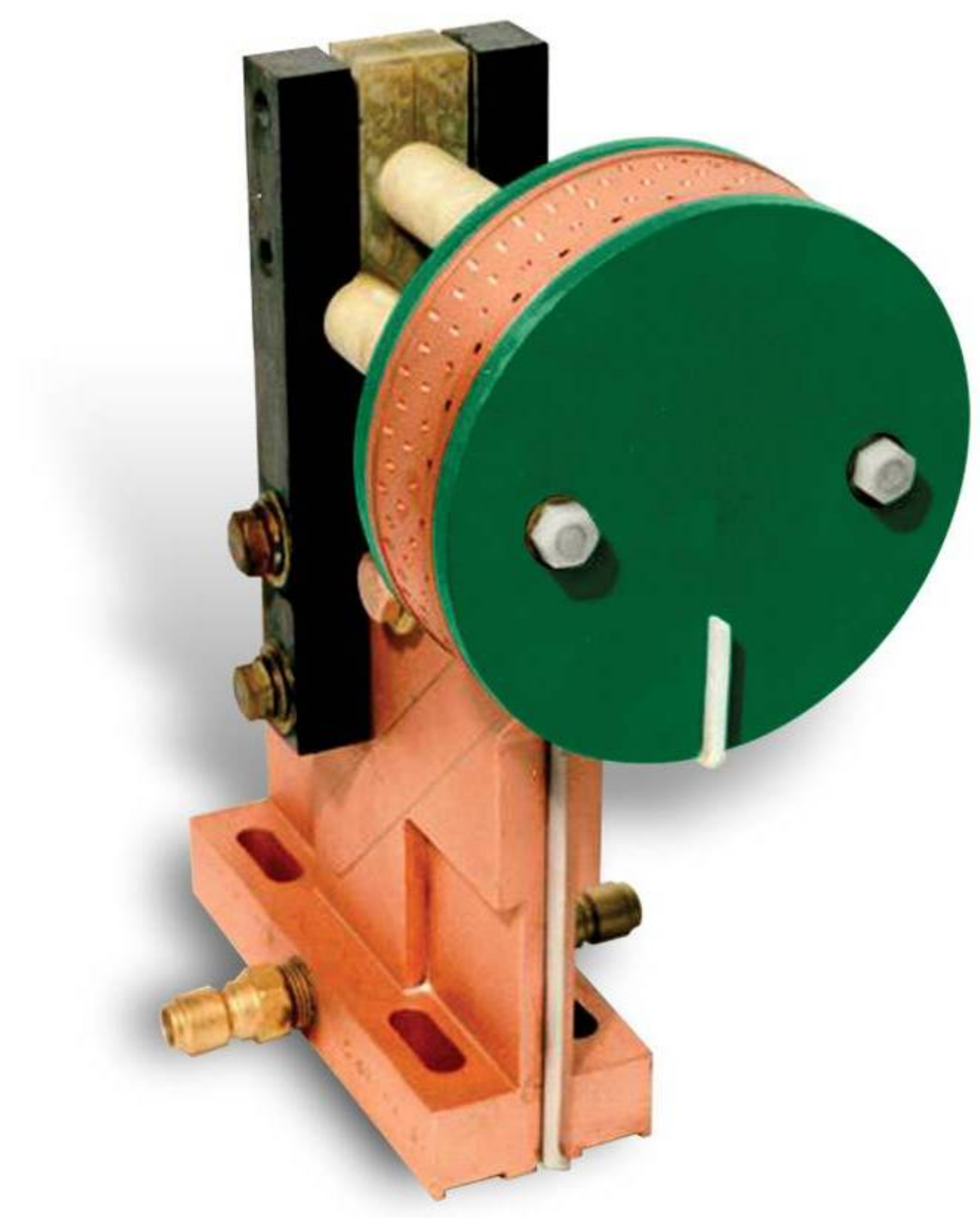
Effects of Magnetic Flux Controllers on I.D. Coils

- In ID coils magnetic flux must return back around the turns in narrow space inside the coil and therefore magnetic resistance Rm is usually high
- Concentrator (core) dramatically reduces coil current required to push the flux on return path
- When the core is installed, magnetic flux and power are much higher with the same coil current or current demand is much lower for the same power



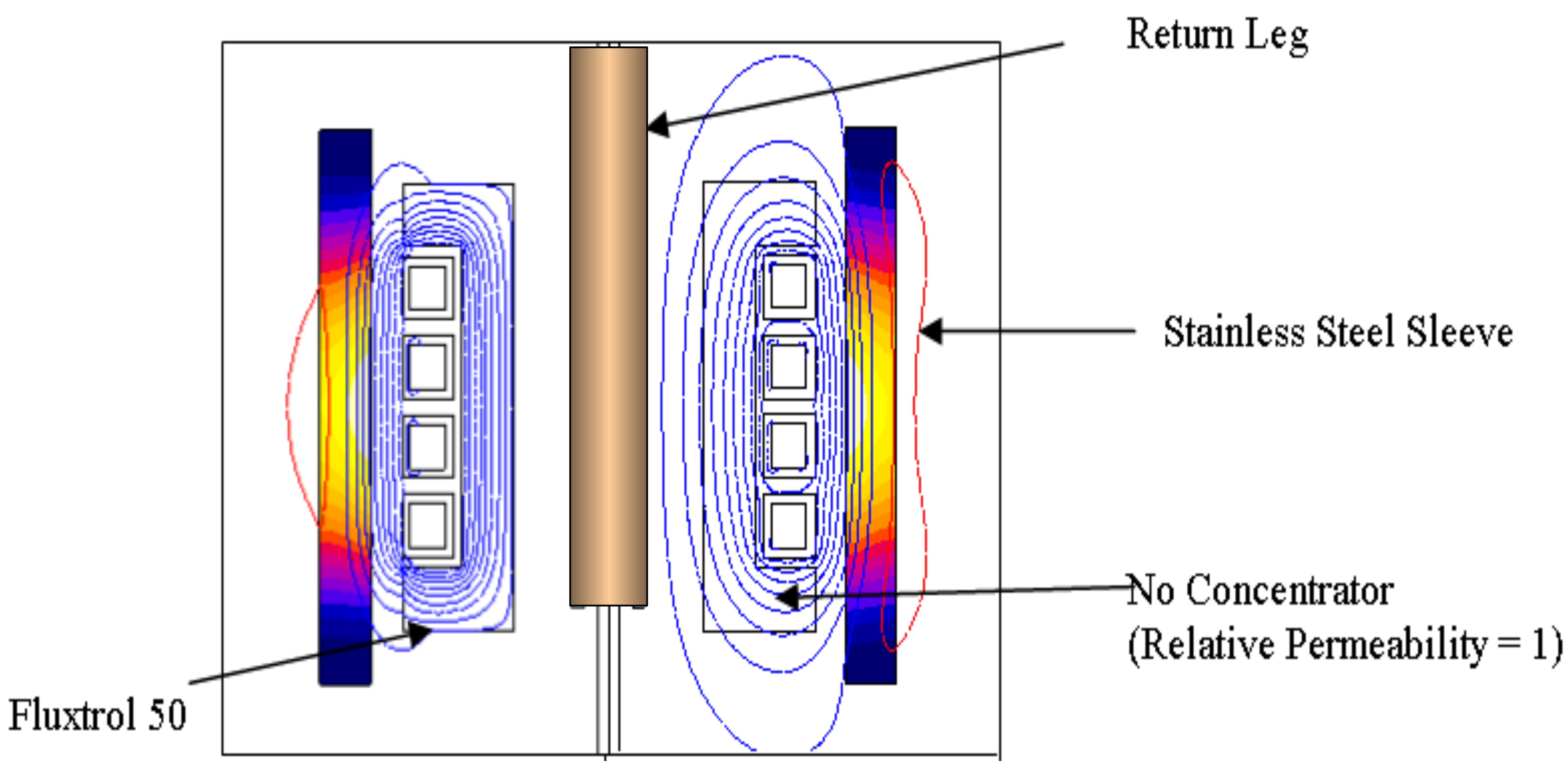
Improvements Expected for I.D. Coils

- Shorter heating time
- Substantial energy savings (oftentimes 40-50% or more)
- Strongly improved electrical efficiency
- Drastically reduced current demand
- Reduced losses in power supplying circuitry
- Heat pattern control



Single-turn I.D. induction coil with Fluxtrol A concentrator

Example of Magnetic Core Influence on Parameters of I.D. Coil



Flux 2D program

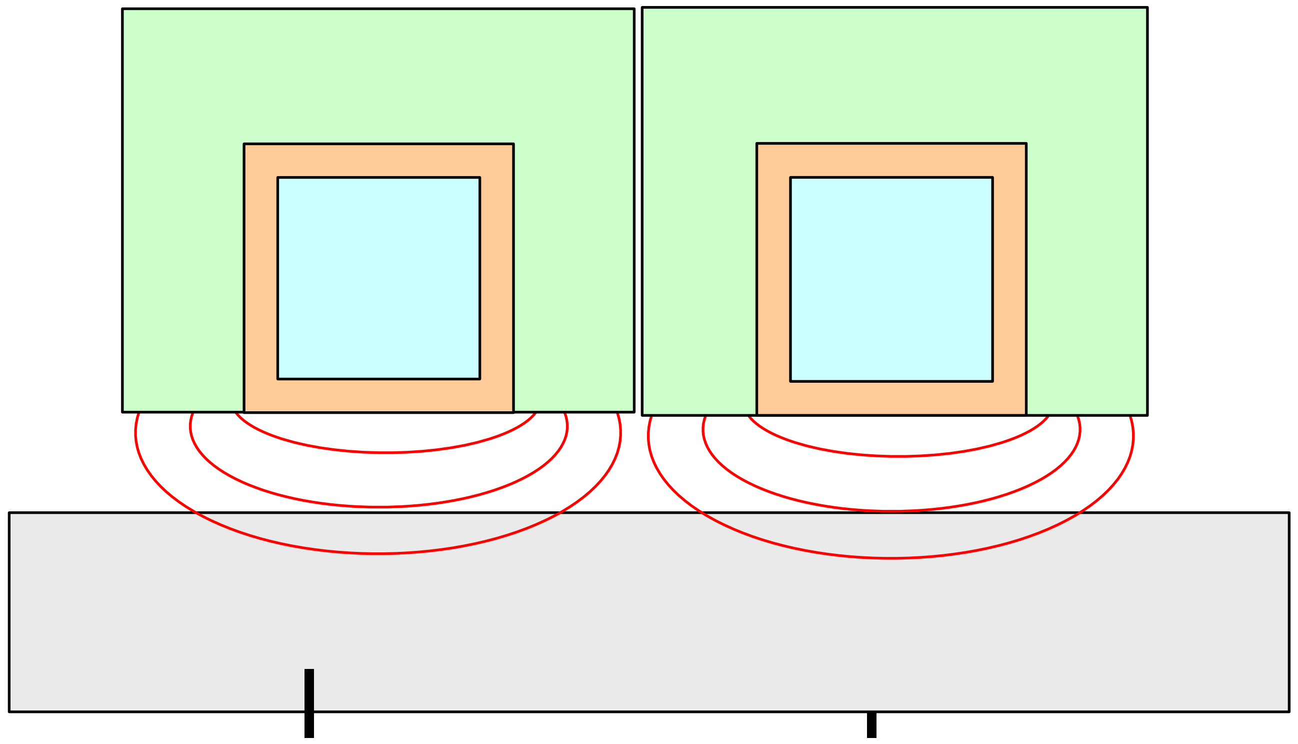
With the same pipe power, application of core reduced coil current from 2000 A to 900 and corresponding reactive power from 65.8 to 30.2 kVAr.

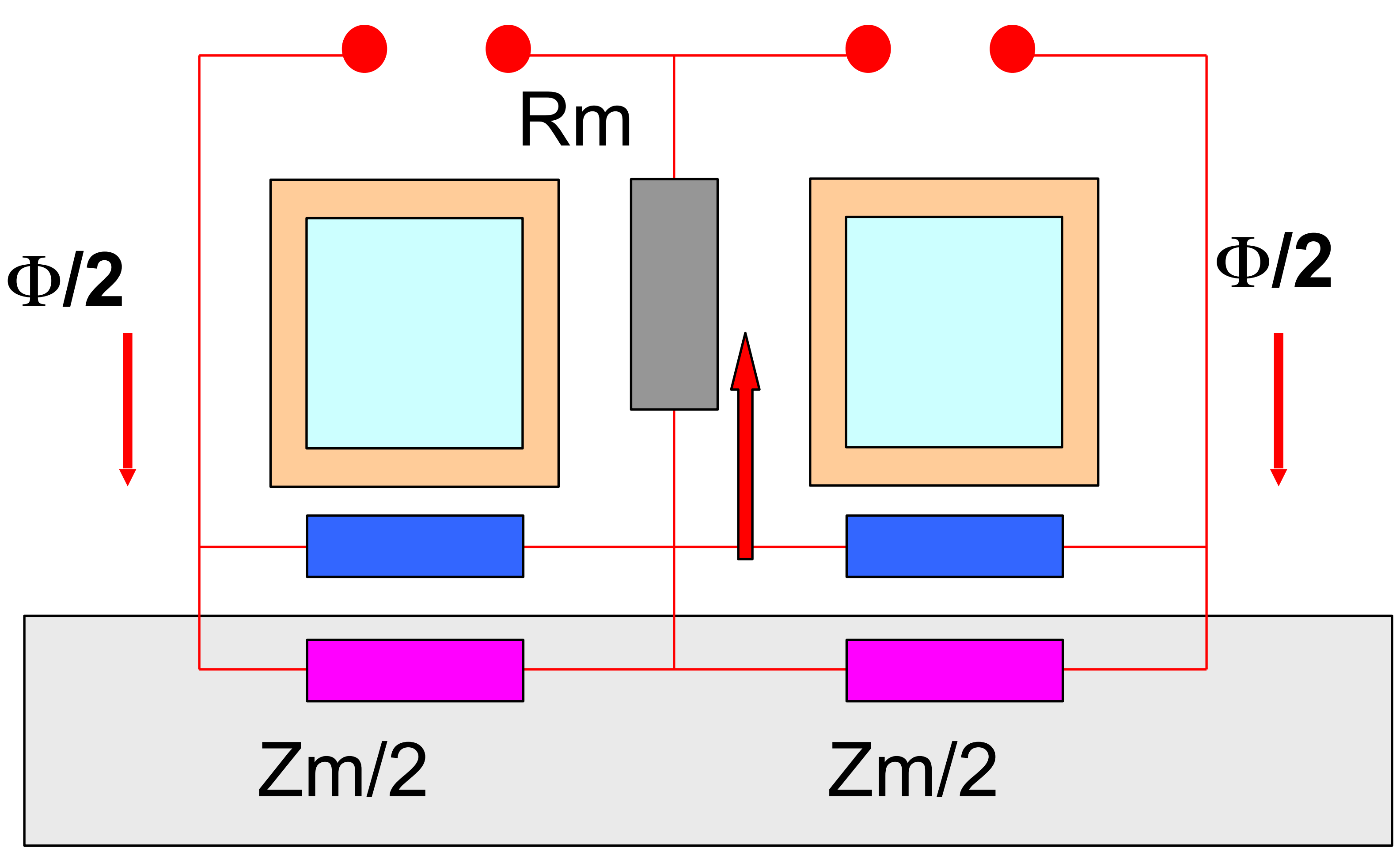
Electrical efficiency of the coil increased from 69% to 84%.

Coil head voltage remained almost the same (5% increase)

Effects of Magnetic Flux Controller on Hairpin Coils

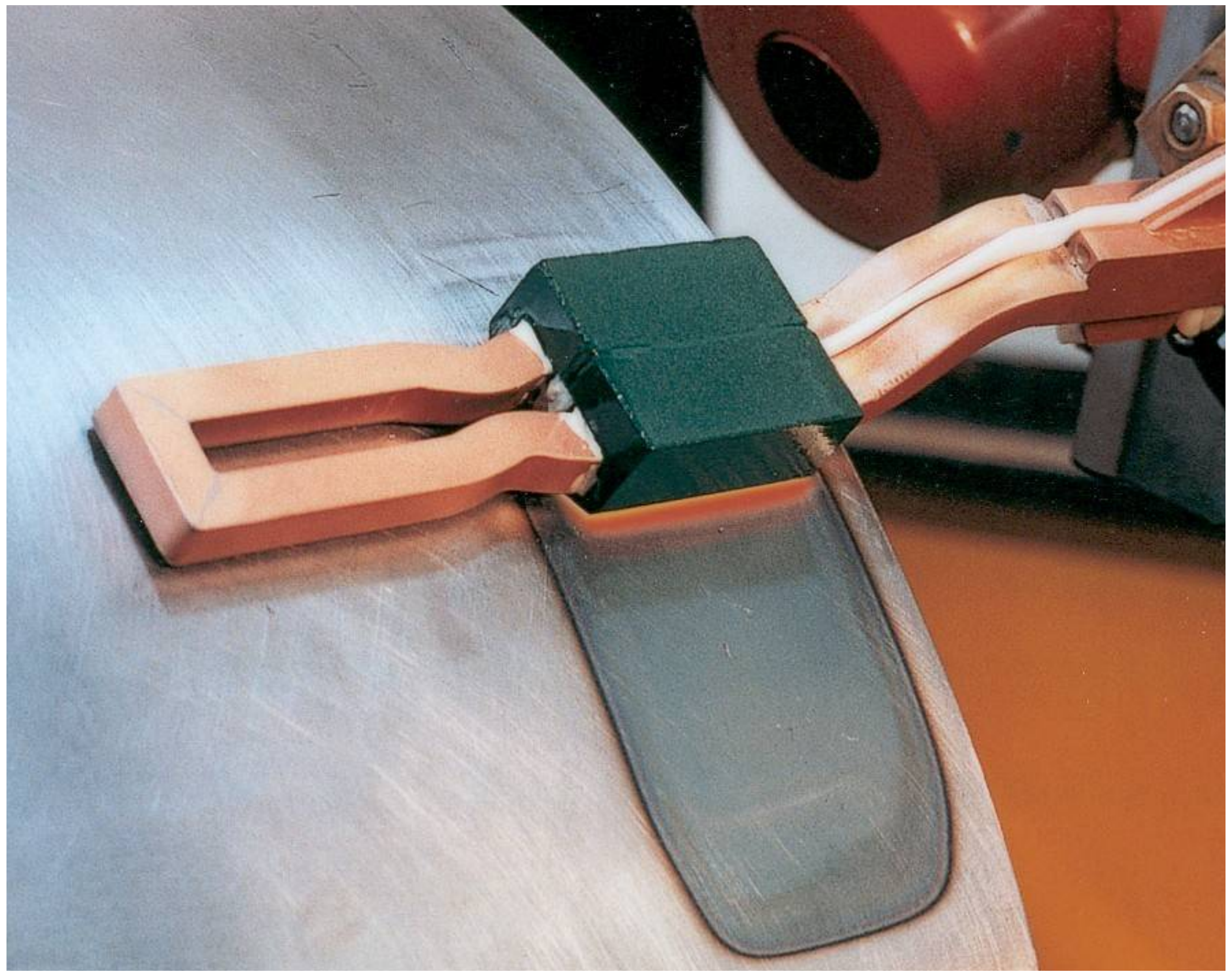
- Magnetic resistance of the back path is mainly due to limited space between the coil legs
- Central pole is critical; side poles are less important though they further reduce current demand
- Application of MFC to a part of the coil provides strong control of power distribution in the part along the coil





Improvements Expected for Hairpin and Transverse Flux Coils

- Shorter heating times
- Substantial energy savings
- Greatly improved heat pattern control
- Drastically reduced current demand
- Reduced losses in power supplying circuitry
- Transverse flux heating - possibility to provide uniform heating in the edge areas



Example of concentrator influence when applied to hair-pin coil (see details on next slide)

Robotic Induction Heating using Hairpin Coil

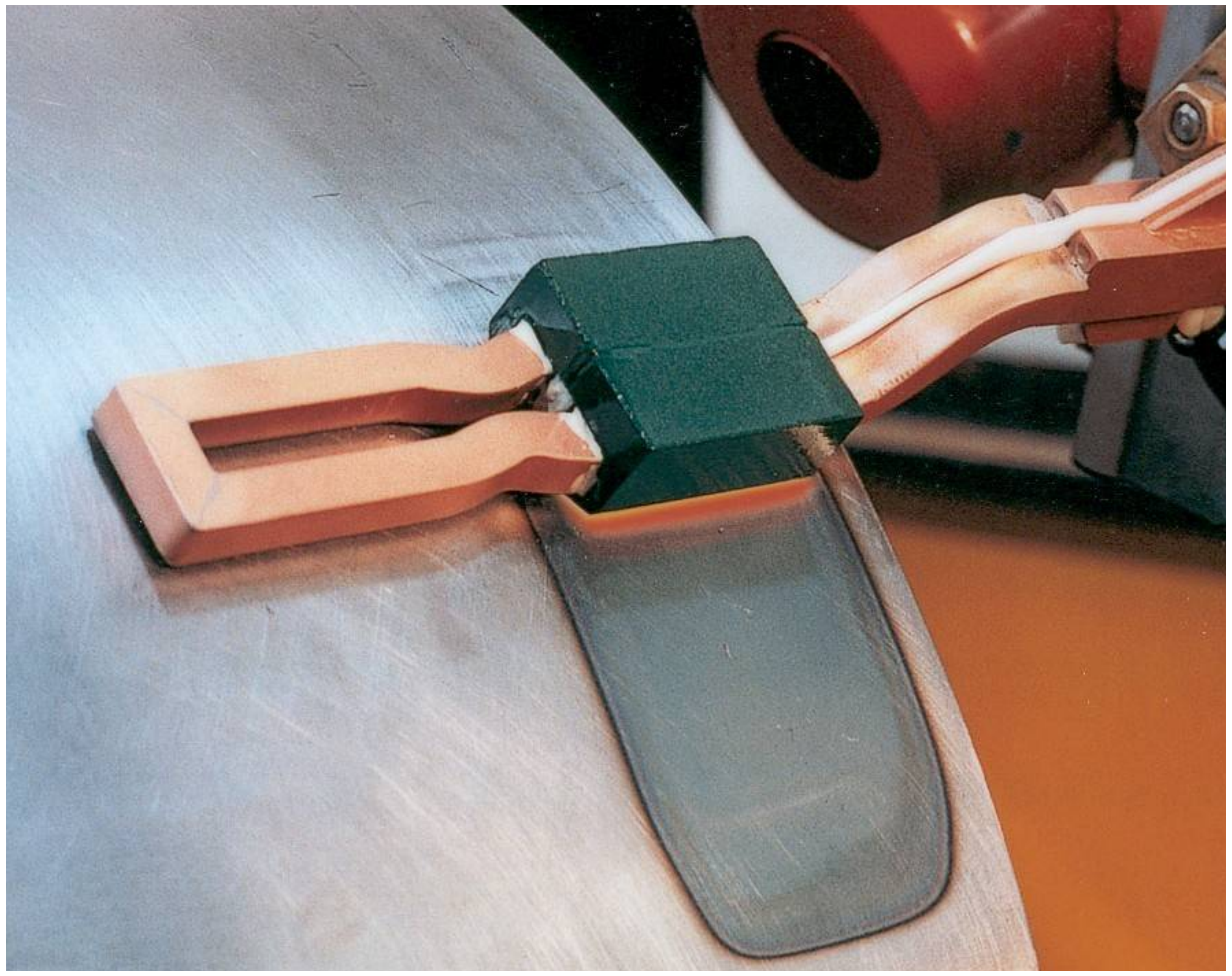
1. Installation:

Power supply – 30 kW, 30kHz Robot – Courtesy ABB

Stand – Stainless steel curved plate with water cooling on internal surface (Special design of Fluxtrol Inc.)

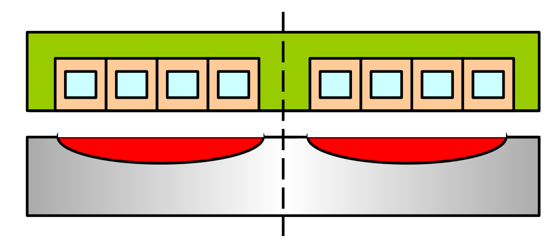
2. Induction coil has two equal sections, one of them has Fluxtrol A concentrator.

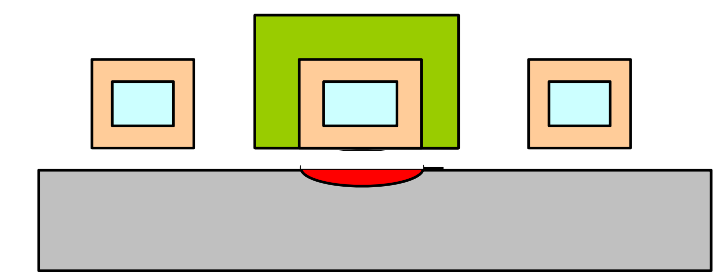
Note: Dramatic difference in heat intensity between coil sections without and with concentrator

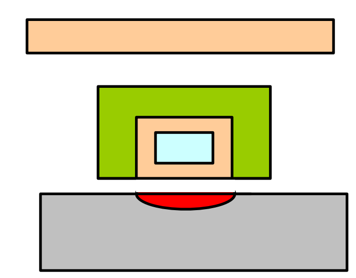


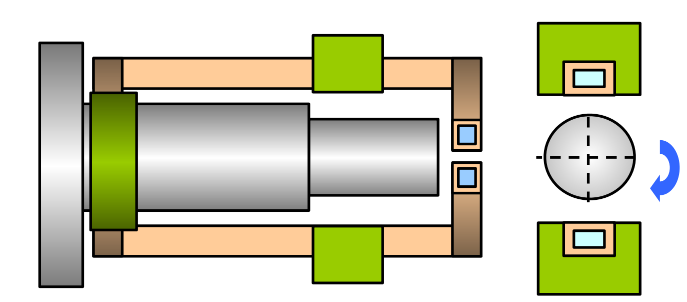
Other Coil Styles Where Concentrators Improve Performance Dramatically

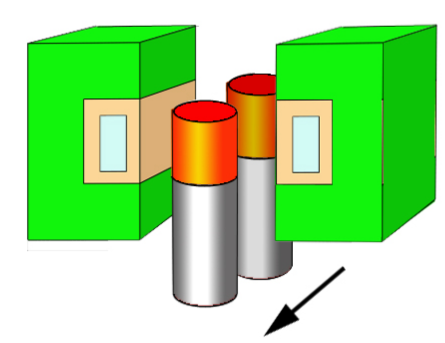
- Pancake Coil
- Split-n-Return
- Vertical Loop
- Single-Shot
- Channel Coils
- Transverse Flux Heating Coils
- Any coil where there is limited space for back path flow of magnetic flux

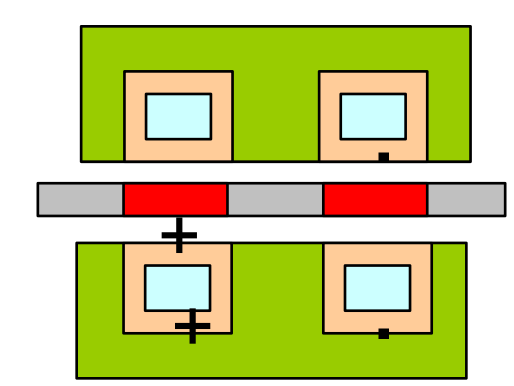








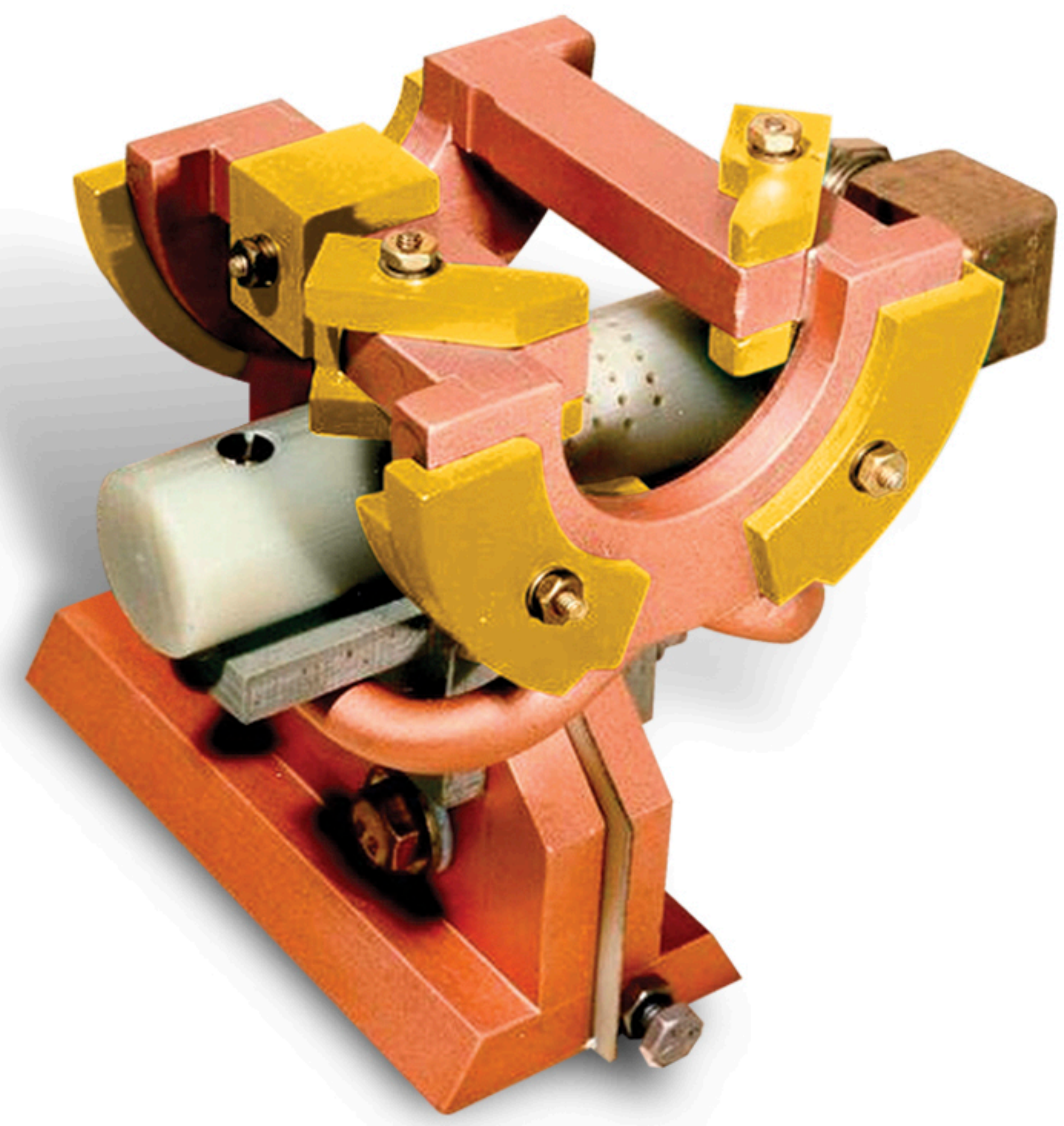




Example: Single-Shot Coil with Fluxtrol 50

Fluxtrol 50 concentrators (yellow) are placed in strategic areas of the coil

Concentrators are mechanically attached to copper while good thermal contact provided by glue



Materials for Magnetic Flux Control

Available materials belong to three major groups:

- MagnetoDielectrics (MD) such as Fluxtrol & Ferrotron materials
- Laminations
- Ferrites

- Magnetodielectrics or Soft Magnetic Composites (SMC) are made of magnetic particles and different binders. Combination of magnetic particle material and size, binder type and manufacturing technology gives a big variety of MD with different properties
- Laminations are thin sheets of special electrical steel with insulation on their surface
- Ferrites are glass-like materials made of oxides of iron, manganese, zinc and other elements

Fluxtrol Inc. produces 3 primary MD materials:

- **Fluxtrol A**
- **Fluxtrol 50**
- **Ferrotron 559 H**

Magnetic Permeability

- For different materials and operating conditions (temperature, magnetic field strength) permeability may vary in a wide range from 1 to several thousands
- Permeability is the main characteristic of material responsible for effects produced by controllers. However, research conducted by Fluxtrol Inc. show that permeability under 100 is sufficient for a majority of induction heating applications (see following slides)
- Materials with low saturation flux density (ferrites) cannot support high permeability at high magnetic loading (B)
- Requirement of high permeability is usually in contradiction to other characteristics such as electrical resistance and machinability
- Influence of permeability on controller performance may be predicted by computer simulation

Simulation Study of Permeability Influence on Process Parameters

Workpiece:

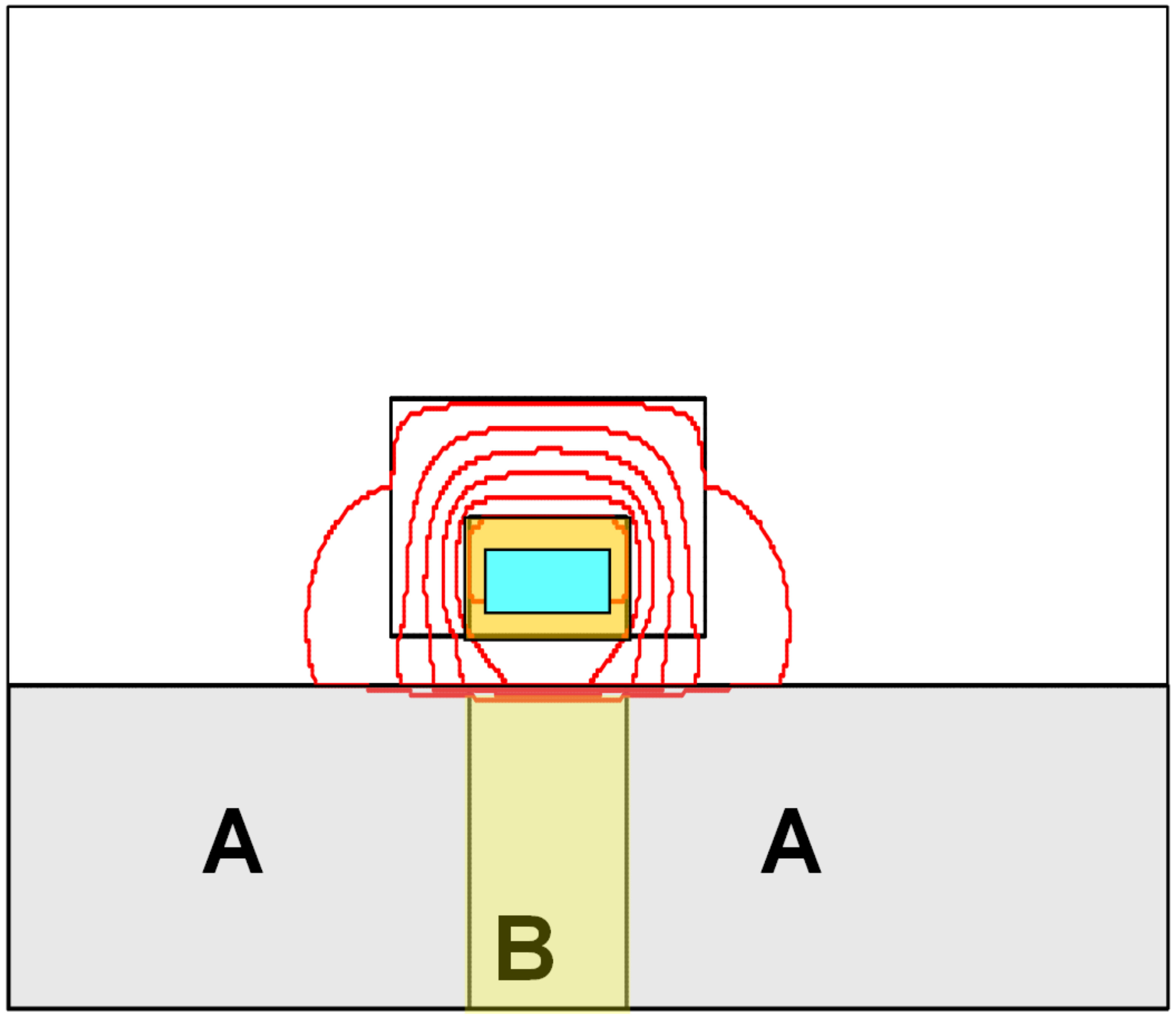
- Flat body composed of a central part B (under the coil face) and two side areas
- Material – magnetic or non-magnetic steel

Conditions:

- Linear single-turn inductor
- Same temperature under the coil face
- Same heating time

Considered parameters:

1. Current demand
2. Power demand

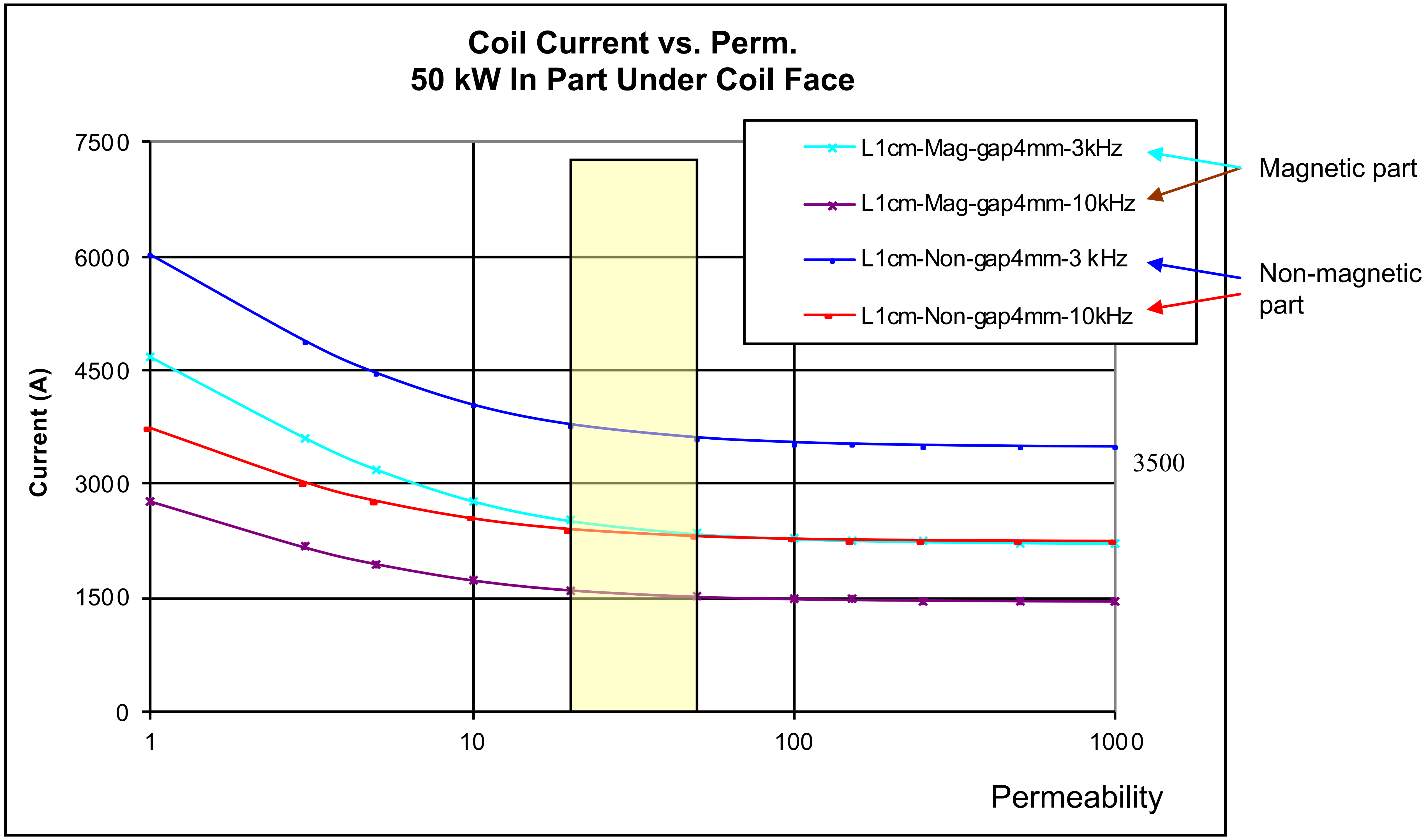


A – side areas, **B** – work area

Gap 4 mm; Coil face width 19 mm

Frequencies 3 and 10 kHz

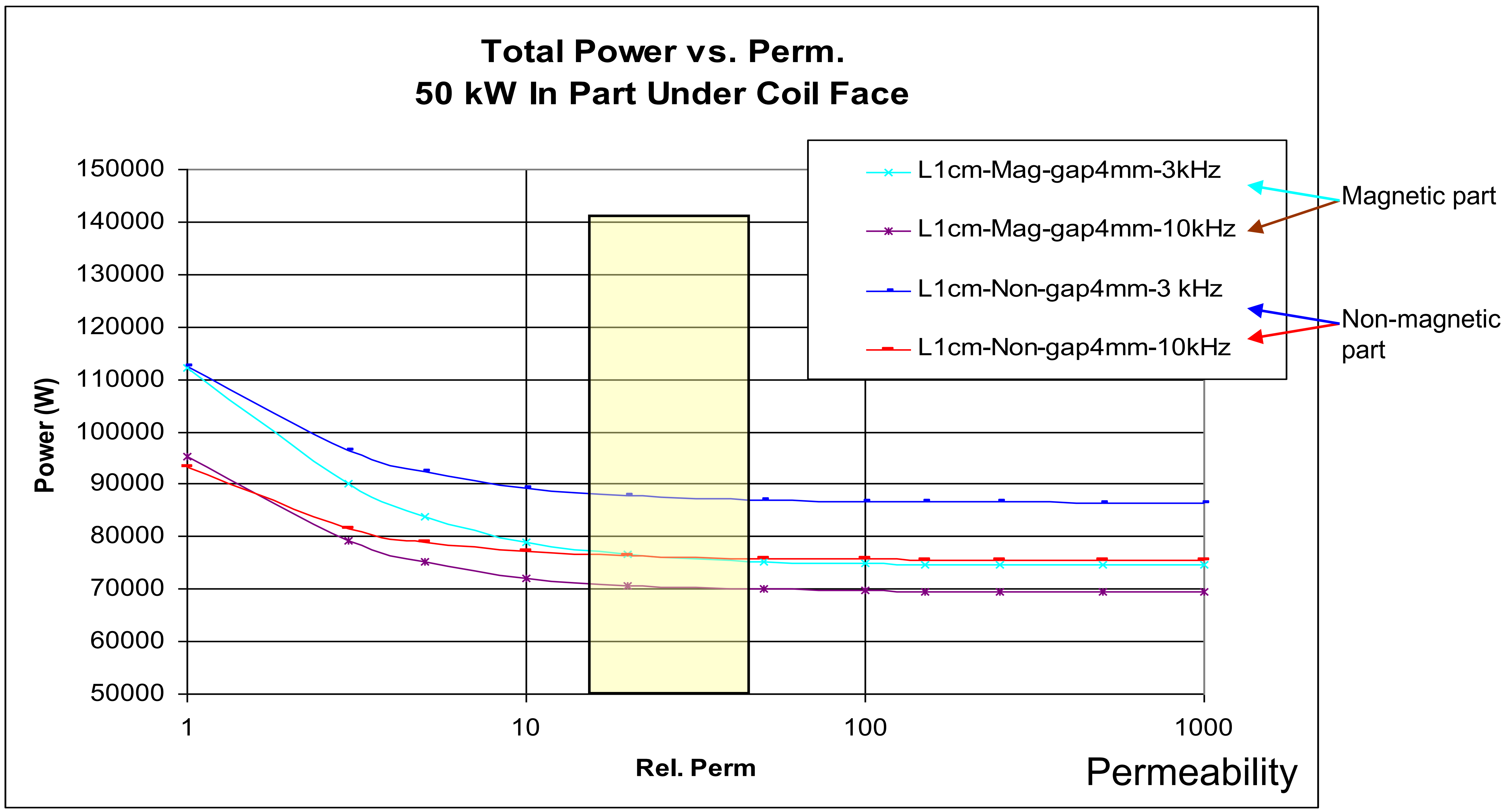
Results: Coil Current Demand vs. Permeability



Concentrator reduces current demand 40 - 50% at permeability 40 - 50 compared to permeability 1 (air).

Notice: very small improvement at higher permeability for all studied cases

Results: Total Power vs. Permeability



Concentrator reduces power demand 25 - 30% at permeability 20 - 40.

Notice: no improvement at higher permeability for all studied cases

Losses in Magnetic Materials

- Losses depend on material type, frequency and magnetic flux density inside the material
- Concentrator losses are usually much lower than losses in the coil copper
- Losses are responsible for concentrator temperature and therefore reliable performance of concentrator
- High thermal conductivity and proper concentrator cooling can keep concentrator temperature under control even when losses are high

There are three types of losses in magnetic materials:

- Hysteresis losses
- Losses due to eddy currents in the concentrator body (“global” eddy currents)
- Eddy current losses in individual components or areas (lamination sheets, metal particles in MD) due to “local” eddy currents.

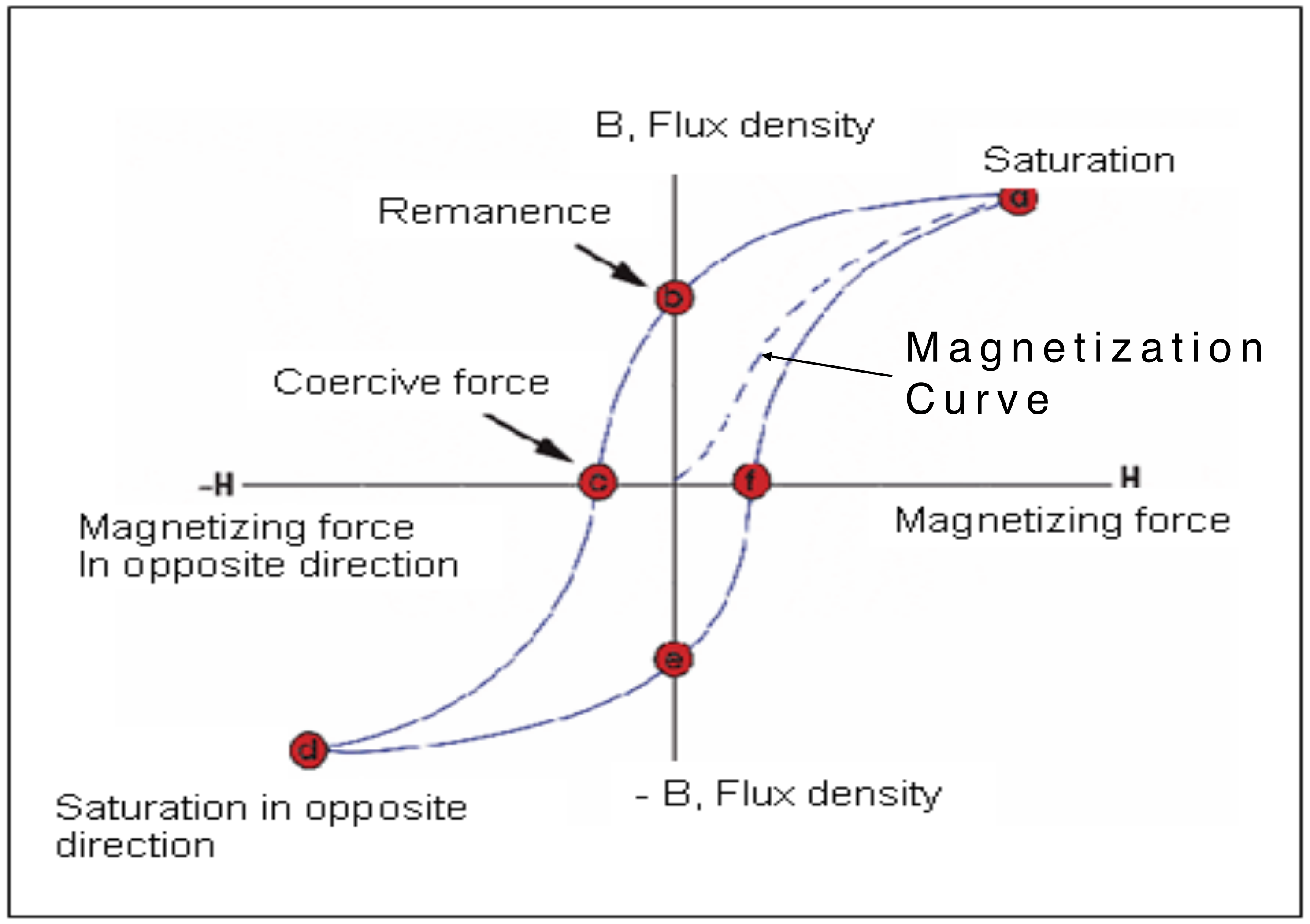
Hysteresis Losses

- Caused by “internal friction” of micro volumes (magnetic domains) of magnetic material in the process of their re-orientation in alternating magnetic field
- Depend on magnetic material nature and operating conditions
- Do not depend on particle size (or sheet thickness) and electrical resistivity of material
- Are approximately proportional to magnetic field frequency
- Annealed materials have lower hysteresis losses
- Hysteresis losses depend upon the area of Hysteresis Loop (next slide)

Hysteresis Loop of Soft Magnetic Materials

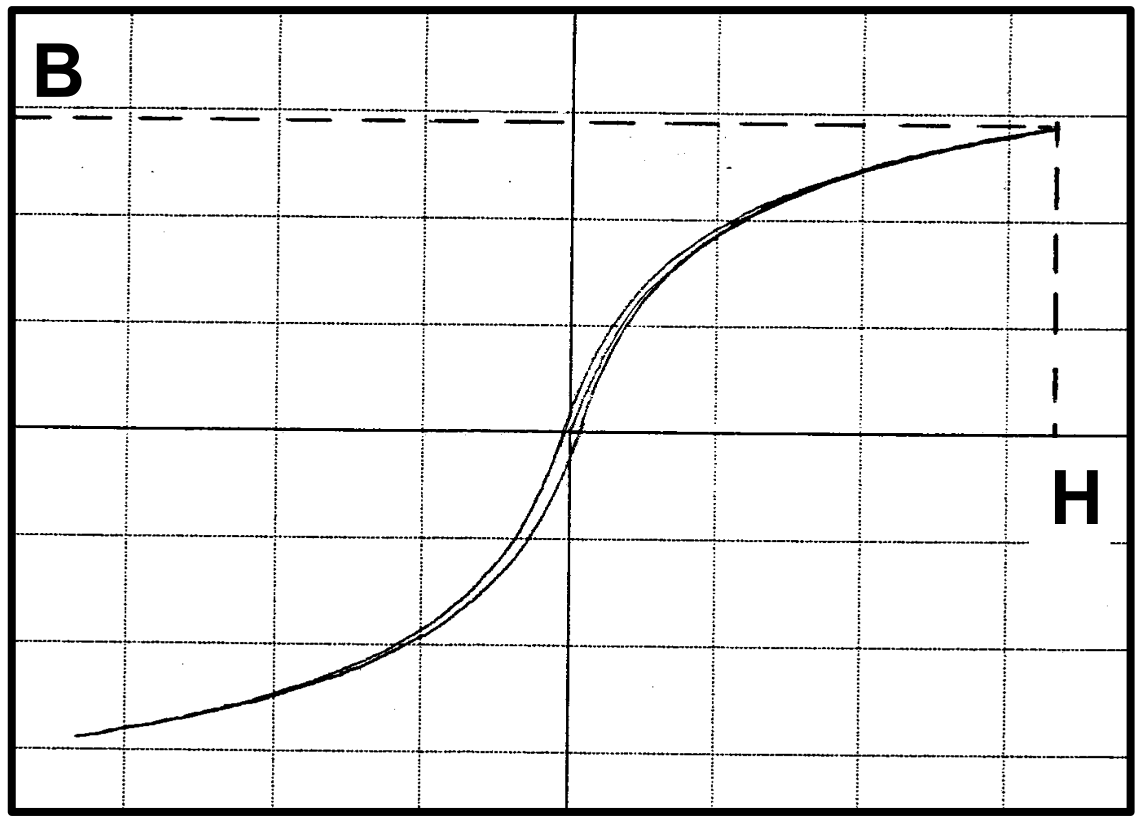
Main magnetic properties may be described by Hysteresis Loop of material:

- Magnetically "soft" materials have a narrow loop with small coercive force. When coercive force is small, the whole loop transforms in one curve (**magnetization curve** of ideal material without hysteresis)
- Magnetization curve reaches a threshold limit – saturation - with strong magnetizing force (i.e. at high value of magnetic field strength)
- Permeability is usually calculated from **magnetization curve** as B/H for each point of the curve
- In case of real materials magnetized by AC magnetic field, B moves along the loop borders (a – b – c – d – e – f – a) when H changes from max to min values
- Magnetic loop is important because magnetic losses for hysteresis are proportional to a product of its area and frequency
- See more information about terms in magnetics in Glossary



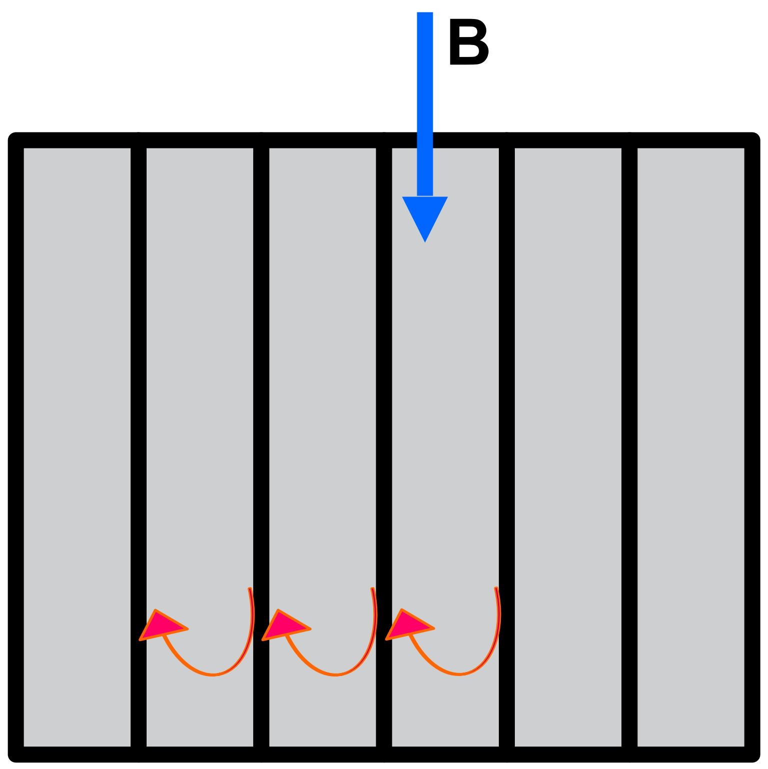
Hysteresis loop of "soft" magnetic material. Width of the loop is enlarged here for better visualization

Real hysteresis loop of Fluxtrol 25

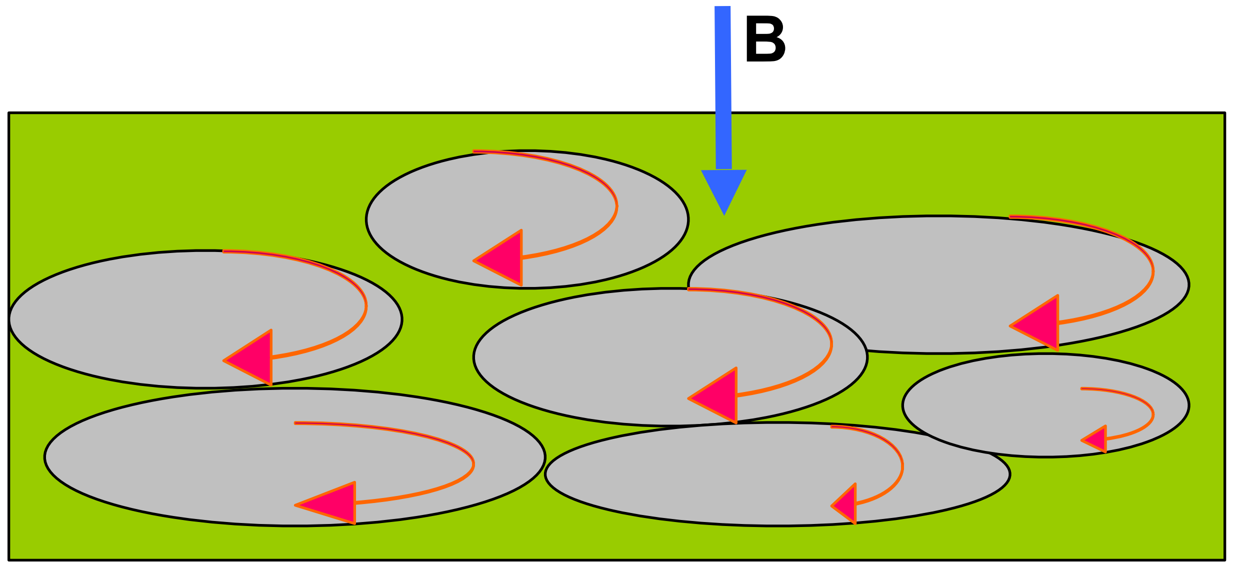


Local Eddy Current Losses

- In Laminations:
  - depend on frequency, steel grade, sheet thickness and their orientation in magnetic field
- In Magnetodielectrics:
  - depend on frequency, magnetic particle size and orientation (for non-round particle shape)
  - depend upon resistivity and permeability of the particle material
- Local losses are approximately proportional to magnetic field density square and frequency square
- For higher frequency, particle size or sheet thickness must be smaller to keep losses under control



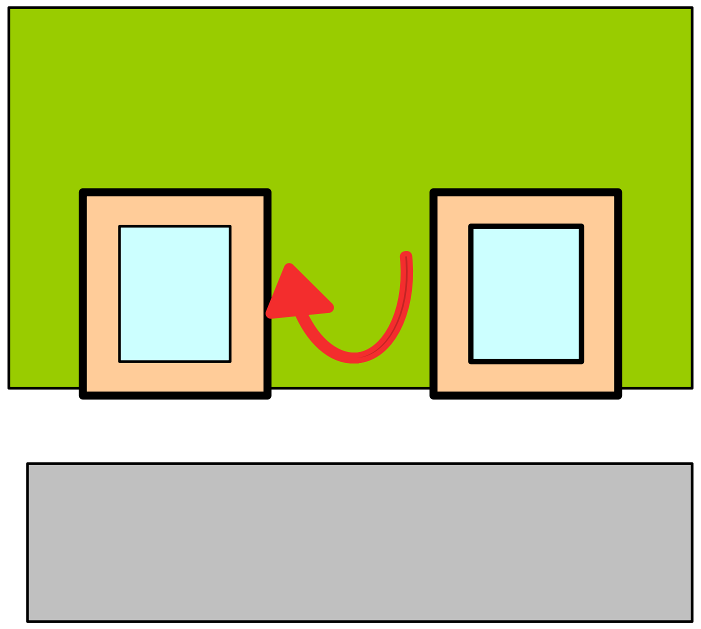
Local eddy currents in laminations

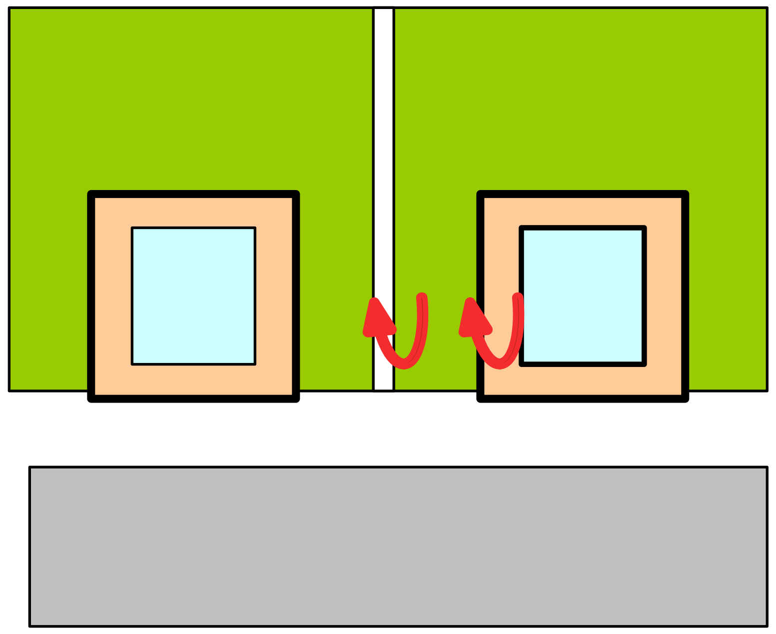


Local eddy currents in magnetic composite particles

Global Eddy Current Losses

- Depend on the **concentrator size** and shape
- Depend on the "global" electrical resistivity of material
- Depend on magnetic field frequency square
- May be reduced by electrical separation of individual parts of concentrator if necessary
- When surface conductivity due to particle smearing is high, etching eliminates additional losses (see slides on etching)

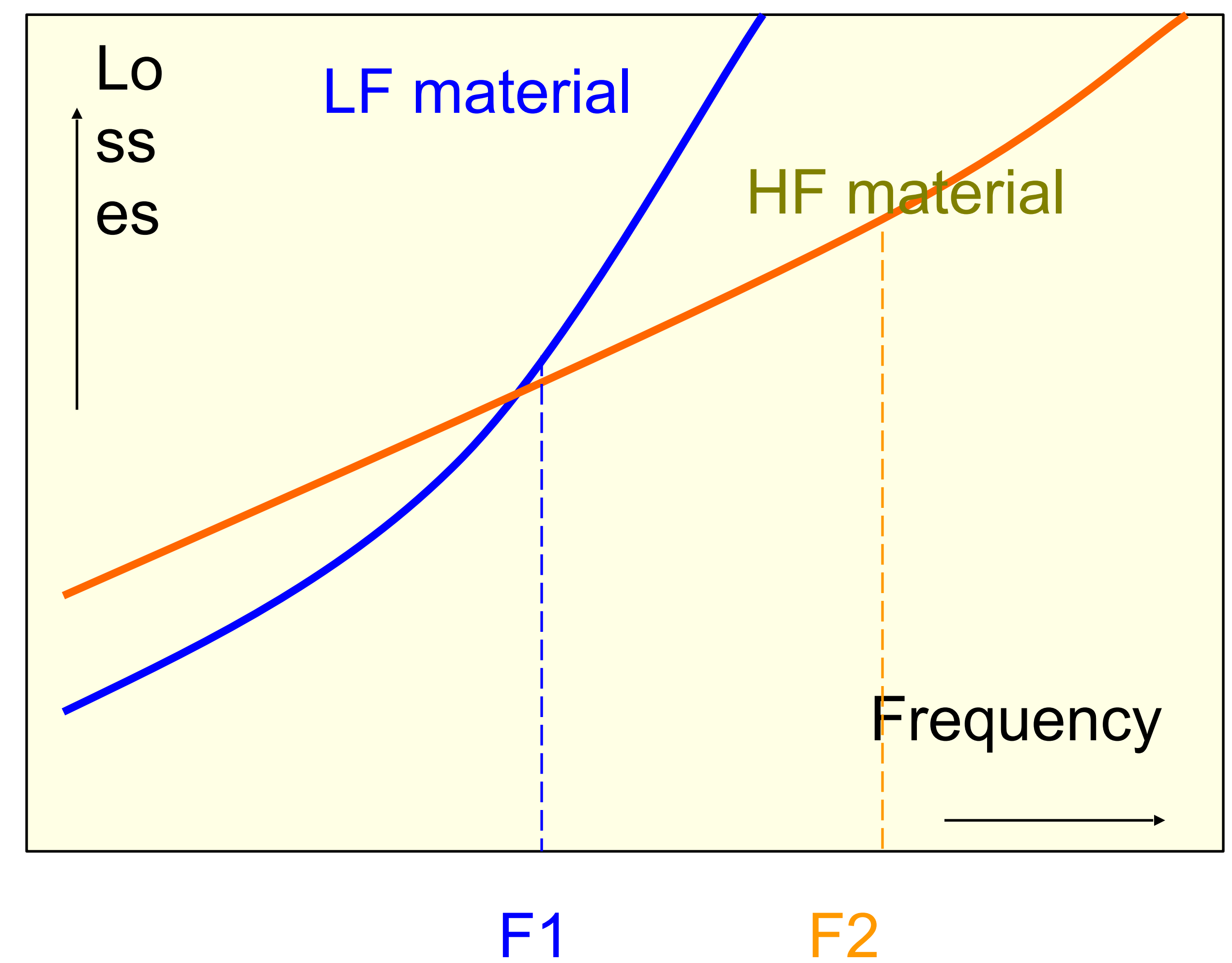




Insulation layer prevents conductor short – circuiting through the concentrator and may reduce losses due to "global" induced current

Dependence of Total Loss Upon Frequency and Flux Density

- For the same flux density losses always grow with frequency
- For low frequency they are proportional to frequency (hysteresis losses)
- For high frequency range they are approximately proportional to frequency square (eddy current losses)
- Losses depend on flux density B square (B^2)
- Material selection must take into account both material losses and thermal conductivity for their removal in order to keep under control the concentrator temperature

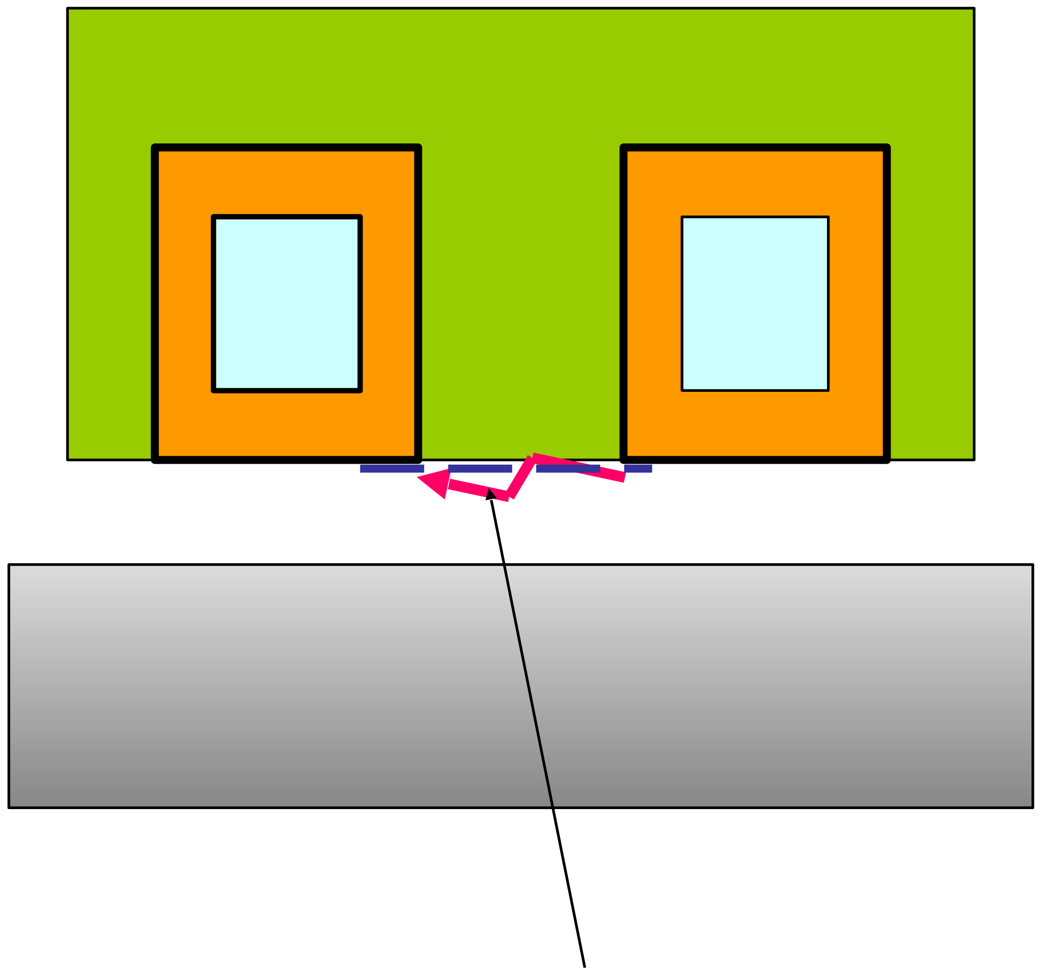


Total losses in two magnetic materials for a given flux density

F1, F2 – recommended frequency limits

Electrical "Resistance" of Composite Material

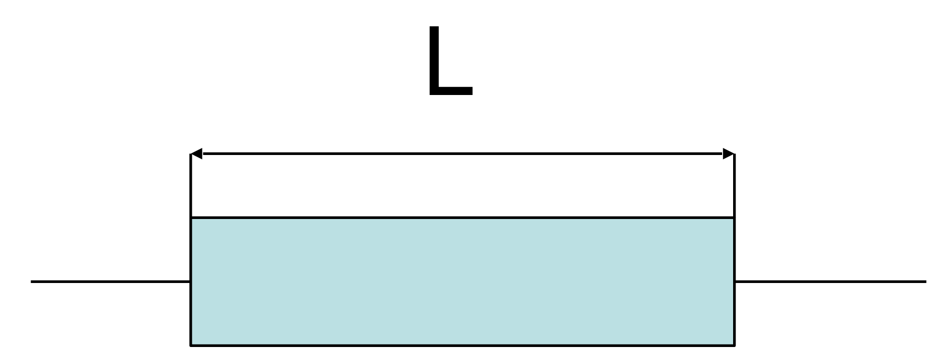
- **Higher The Better! But high resistance is in contradiction to magnetic and thermal properties…**
- Depends on material type and surface conditions (as pressed, machined, ground, sand-blasted,…)
- Insufficient resistance can result in:
  - Possible short circuiting between the coil turns through the concentrator
  - Loss increase due to induced "global" eddy currents



Coil short circuiting along a conductive surface of concentrator

Resistance and Resistivity

- In general Resistance is a parameter of electrical component (resistor)
- When applied to a piece of any material, it is a resistance of the whole piece. It depends on a body size, dimensions and material property (Resistivity). Resistance will also depend upon the points of application of measuring device contacts and local contact resistance
- Resistivity ρ is a characteristic of material, not of a body; it equals to resistance of material volume unit
- To calculate resistivity, resistance of a piece of material with a regular cross-section must first be measured
- Resistivity equals to a body resistance divided by its length and multiplied by cross-section; measured in Ohm cm or Ohm inch (see next slides on resistivity measurement)



S - sample cross-section

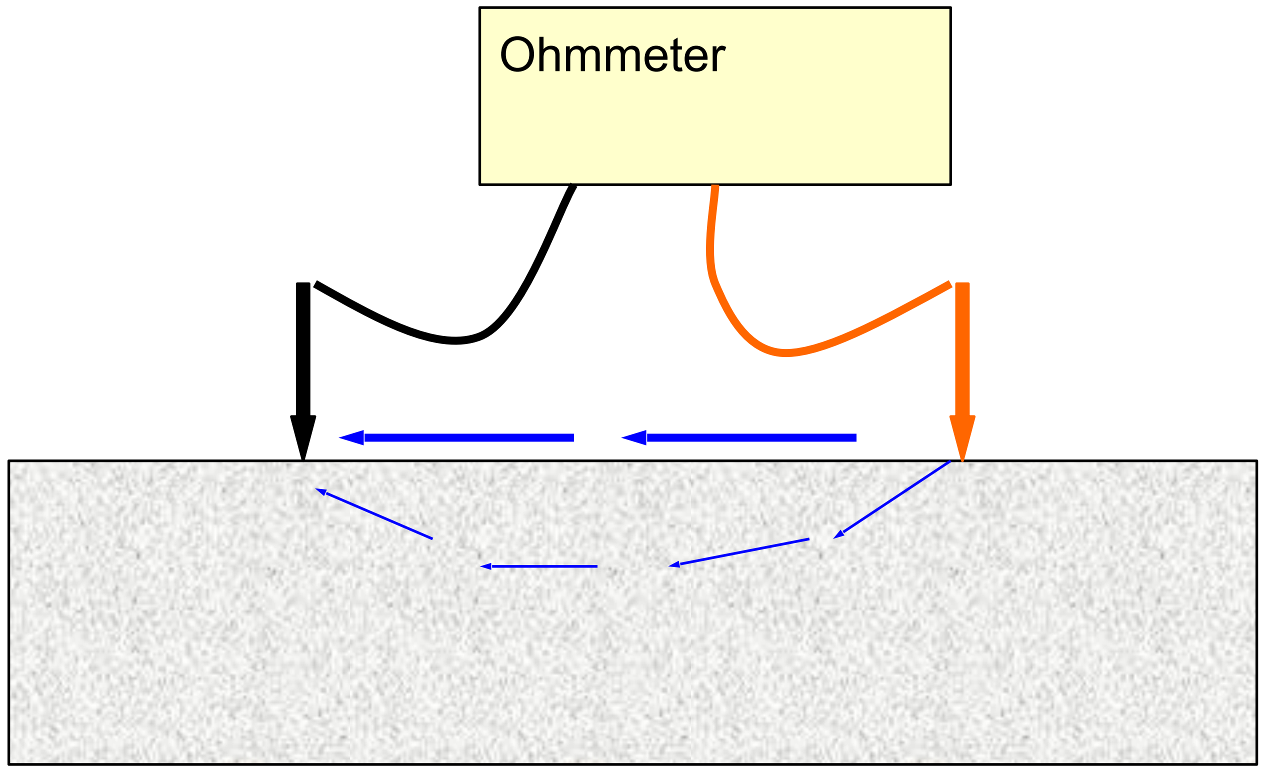
R – electrical resistance

Resistivity

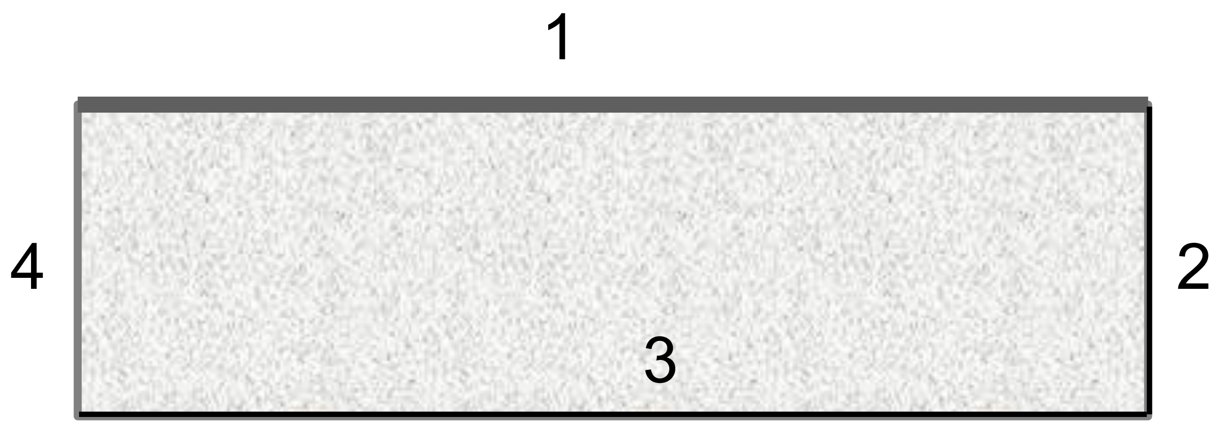
$$\rho = RS/L$$

"Touch" Resistance

- It is a common practice to apply contacts of Ohmmeter (Multimeter) to a piece of material and measure resistance. It may be called "touch" resistance
- Touch resistance **may only be** used for diagnostic and material identification purposes
- Touch resistance **may not be** used for calculation of resistivity because of influence of contact area resistance and uncertain path of current flow in cross-section
- Touch resistance depends, also, on a surface where contacts are applied. It is maximum on a broken ("virgin") surface and may be many times less on pressed and machined surfaces due to a conductive surface layer formed by particle smearing and insulation damage
- Material etching removes conductive layer and increases surface touch resistance
- **Never use high voltage Insulation Tester to measure touch resistance. High applied voltage (more than 1000 V) may break material insulation and readings may be close to zero**



Measurement of "touch" resistance



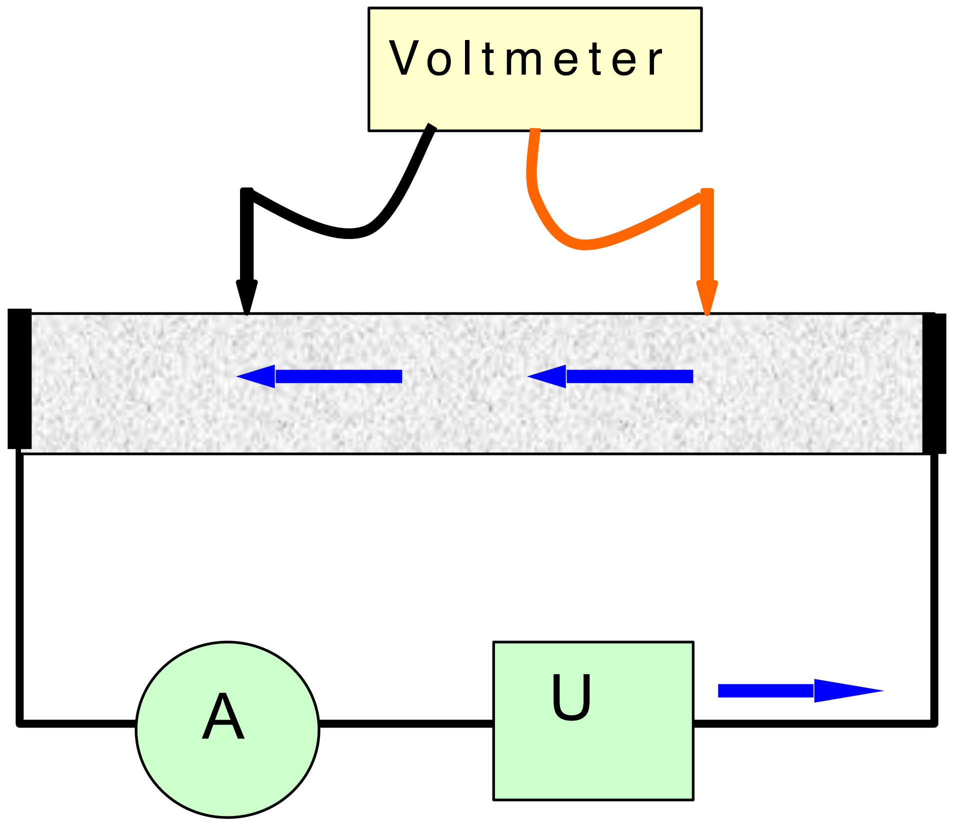
Surfaces:

1 – machined; 2 – side pressed;

3 – bottom pressed; 4 – broken surface

Electrical Resistivity Measurement

- Soft magnetic composites are not conductors nor real electrical insulators; their resistivity is vary in a very wide range depending on material type. Resistivity of Fluxtrol/Ferrotron materials are in a range from hundreds to millions Ohmcm (high frequency materials)
- Fluxtrol Inc. uses 4-point method for measuring resistance and then for resistivity calculation; applied voltage is typically 10-50 V, 60 Hz
- Majority of materials must be etched to remove conductive surface layer prior to resistivity measurements



4-point resistance measurement

Ask company for details

Considerations for Magnetic Controller Material Selection

Electromagnetic characteristics:

- Magnetic permeability
- Saturation flux density
- Electrical resistivity
- Losses
- Operating frequency

Thermal characteristics:

- Thermal conductivity
- Temperature resistance

Mechanical characteristics:

- Mechanical strength
- Hardness
- Machinability

Others

- Ease of installation
- Chemical resistance
- Special characteristics
- Overall costs etc.

Importance of individual characteristics strongly depends on application type

Magnetodielectric Fluxtrol Materials

- Properties depend on magnetic particle type and size, binder type and manufacturing technology
- Magnetic permeability may be in a wide range from several units to more than hundred
- Can work in 3D magnetic fields
- Can work in the whole frequency range of induction heating applications
- Fluxtrol and Ferrotron MD materials have excellent machinability
- Due to mechanical properties may be used as structural components of induction coil assembly
- Easy to apply and modify in field conditions
- May be custom designed to meet specific requirements
- Specific properties of Fluxtrol and Ferrotron materials and technology of their application to induction coils are described in the next chapter

Laminations

- Very high permeability (thousands in weak fields)
- High temperature resistance, which depends mainly of electrical insulation of sheets
- High saturation flux density (1.8 T)
- **Limited to low frequency (below 30 kHz)**
- **More difficult to provide intensive cooling**
- **Application is very laborious especially for complex coil geometry**
- **Difficult to machine**
- **Poor performance in 3-D fields**
- **Rusting and expansion/deformation when overheated**

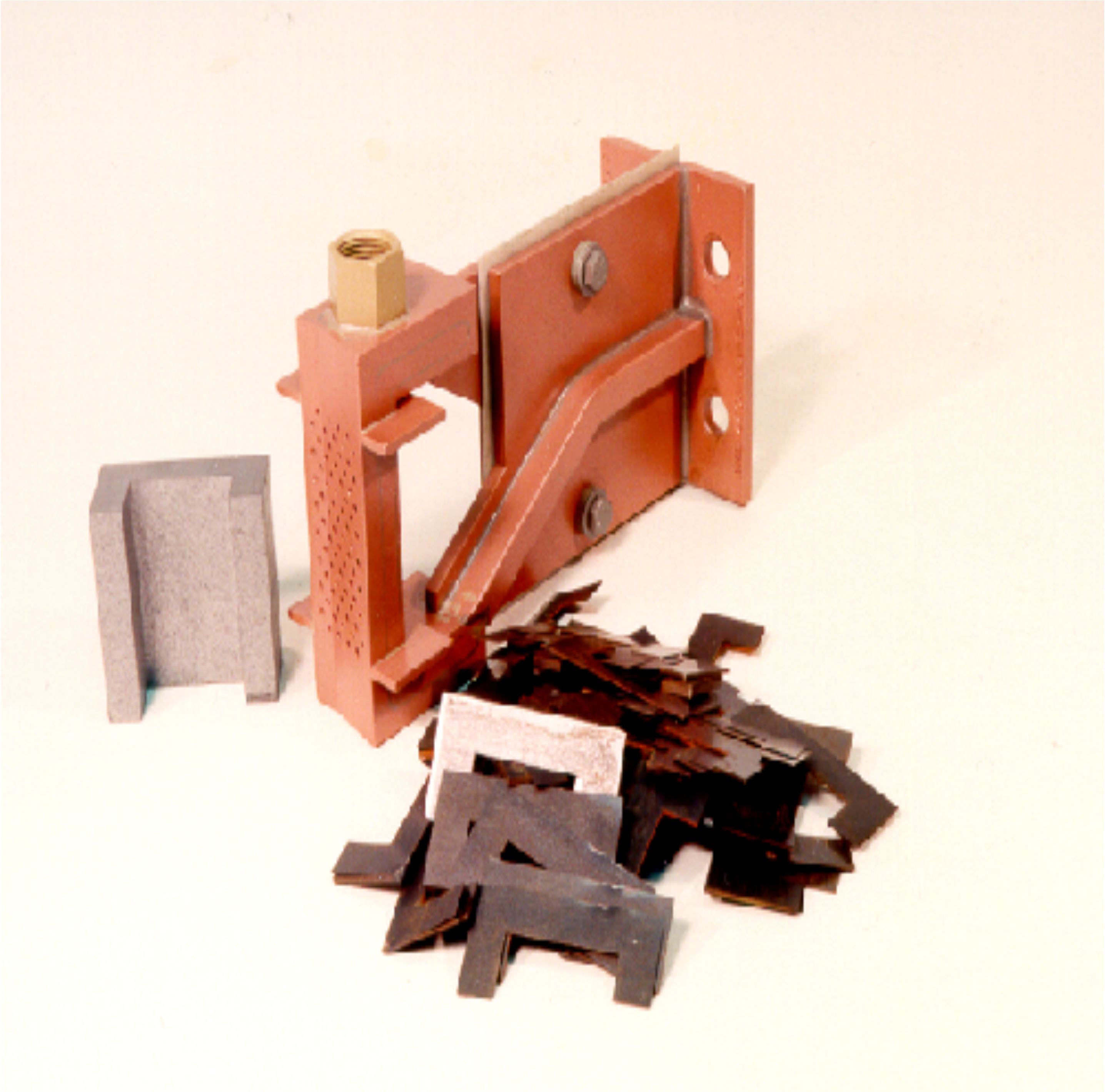
Ferrites

- High permeability in weak fields (up to tens of thousands)
- Can work at high frequencies
- Low losses in selected grades
- **Low saturation flux density (0.3-0.4 T)**
- **Low Curie temperature (~ 250 C) with magnetic properties reduction starting at 150-200 C**
- **Poor thermal conductivity**
- **Very poor mechanical properties**
  - **High hardness**
  - **Brittle**
  - **Non machinable with conventional tools**
- **Sensitive to mechanical impacts and thermal shocks**
- **Inconsistent dimensions (large tolerances) from manufacturer**

General Guidelines for Selecting the Right Type of Concentrator Material

Determine requirements and conditions for a given application

- Induction coil geometry
- Magnetic properties of material
- Frequency, power and duty cycle
- Lifetime of inductor
- Time to get material
- Time to manufacture coil
- Costs of materials
- Costs of material application
- Ability to reproduce coil easily



Vertical Loop induction coil with a pile of laminations and Fluxtrol block

Conclusions

- Magnetic flux control is an important part of optimal design of induction coils; their application must be considered at the stage of induction system development
- Magnetic controllers may play different role (power profiling, concentration, current reduction, shielding etc.) depending on application
- Controllers can fulfill several functions simultaneously in one induction system
- Application of magnetic controllers reduces coil current and reactive power resulting in better performance of power supply; in some cases smaller and less expensive power supply may be used
- Computer simulation and practical experience show that permeability increase above 60 – 100 does not improve controller performance
- Magnetic controllers may be made of magnetodielectric materials (Fluxtrol soft magnetic composites), thin steel sheets (laminations) or magnetically soft ferrites
- Laminations may not be used at high frequency due to big losses and poor performance in 3D magnetic field
- Ferrites have low saturation flux density, low Curie point, poor thermal and mechanical characteristics
- Magnetodielectric materials can provide a combination of magnetic, electrical, thermal and mechanical properties favorable for induction heating applications

Questions / Answers

- Application of Flux Controllers can provide what type of improvements?
  Heat Pattern, Coil Efficiency, Power Utilization, Current Demand, Coil Life
- Applying Flux Controllers reduces what portion of this magnetic circuit formula $\Phi = IN/(Zm + Rm)$?
  Rm - back path magnetic resistance (reluctance)
- On I.D. coils the path for the magnetic flux return is usually restricted therefore magnetic resistance Rm is?
  High
- What is the main material property responsible for the effects of Flux Controllers?
  Permeability at work conditions
- Permeabilities of what number are sufficient for most induction heating applications?
  Less than 100 (less than 50 in majority applications)
- What are the 3 types of losses in magnetic materials?
  Hysteresis, Global Eddy Current, Local Eddy Current
- Insufficient electrical resistivity of materials used in Flux Controllers can result in?
  Short circuiting between coil turns, increased losses
- Materials used for magnetic flux control can be organized into 3 main groups, those groups are?
  Magnetodielectric, Laminations, Ferrites
- Laminations perform poorly in what magnetic fields?
  3D magnetic fields
- Laminations are limited in frequency to?
  Low Frequency
- When Lamination overheat what can occur as a result?
  Rusting, Deformation
- Ferrites have what type of mechanical properties?
  Brittle, Very hard to Machine
- Ferrites have Curie temperatures that can be characterized as being?
  Low

FLUXTROL®