Specification and Use of a Flux Concentrator

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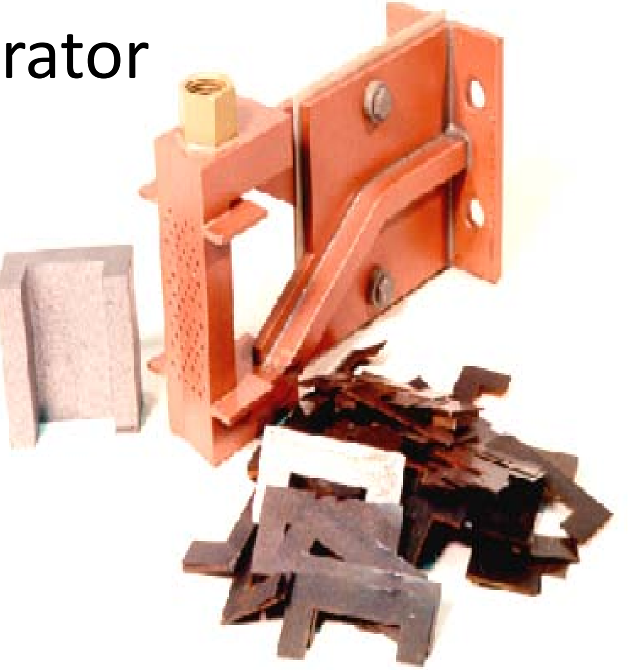
Overview

- Basics of Magnetic Flux Control
- Effect of Flux Controllers on Different Coil Styles
- Materials for Magnetic Flux Control
- Influence of Magnetic Permeability
- Selecting the Proper Flux Concentrator
- Example:
  - Crankshaft Hardening Inductors
- Conclusion



What is Magnetic Flux Control?

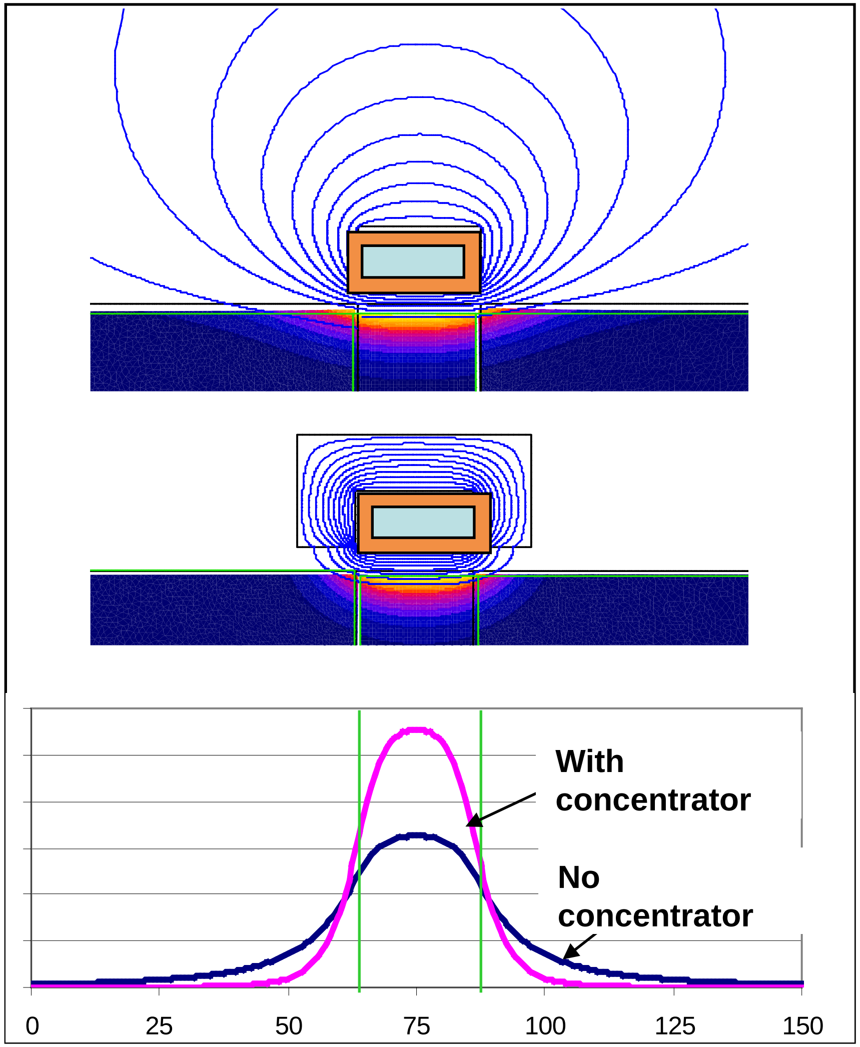
- Magnetic flux control is a generic term for modification of induction coil magnetic flux by means of installation of magnetic templates (magnetic flux controllers)
- Magnetic controllers may significantly change magnetic field pattern and coil parameters; their application must be considered as a part 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

Magnetic Flux Controller Effects

Effects:

1. Reduction of external field
2. Higher power in the part at the same coil current
3. Power concentration under the coil face
4. But… the coil current is concentrated on one side of the coil tubing resulting in higher losses

Analysis can predict all the results.



Power distribution on the part surface for same coil current

Possible Improvements due to Magnetic Flux Controllers

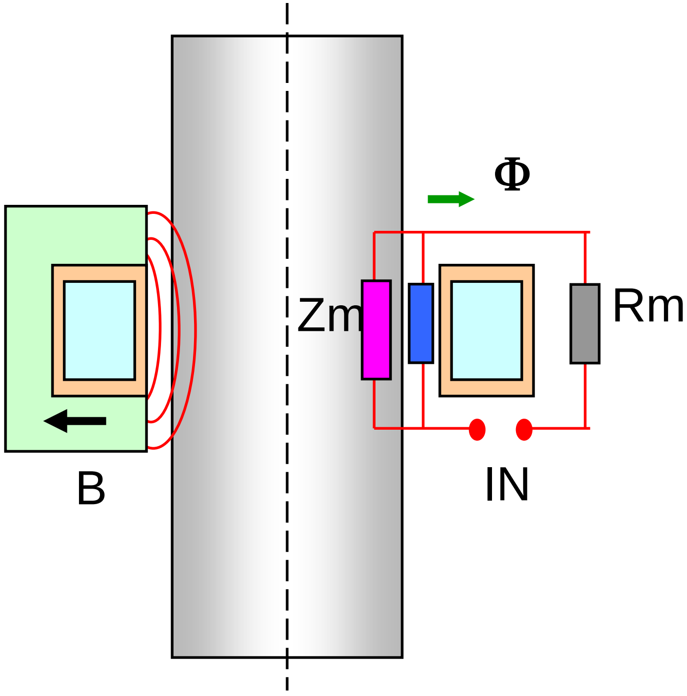
- Precise heat pattern control
  - Reduced Distortion
  - Improved Part Quality
- Energy savings
- Production rate increase
- Longer Power Supply, Transformer, Capacitor and Bussbar Lifetime
  - Due to reduced current and kVAR. Improvement in power factor (cosØ) has a large impact on the losses in these components
- Shielding of part or machine components from unintended heating

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

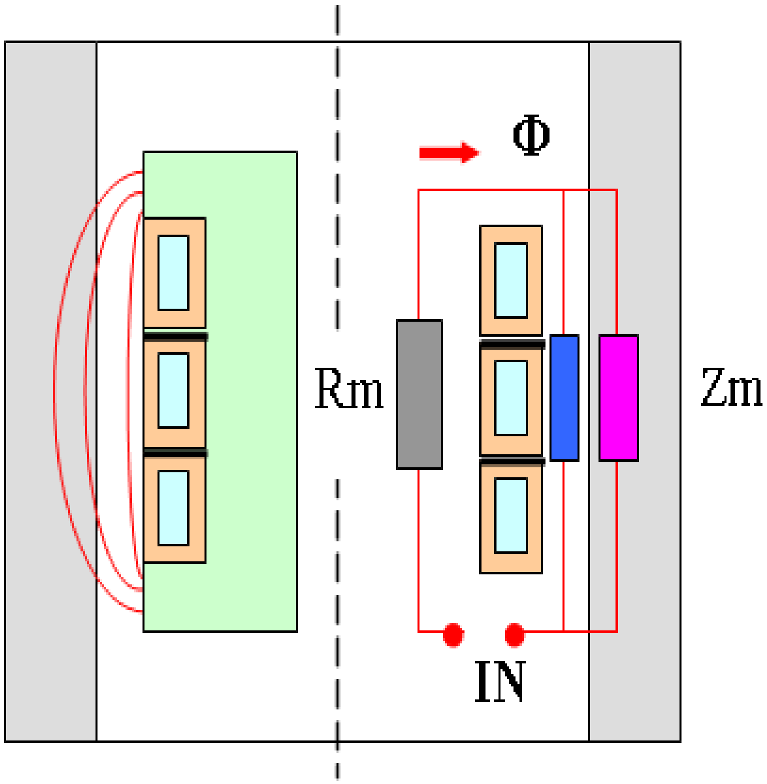
- Improved Heat Pattern Control /Ability to Heat Difficult Areas (axle fillet, etc.)
- Better Utilization of Power in Workpiece for short static coil (energy savings up to 30%)
- Lower Coil Current and therefore reduced losses in supplying circuitry – transformer, capacitors, busswork
- Shielding of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

Magnetic Flux Control
Example of ID Coil

Φ = IN / (Zm + Rm)

Φ – Magnetic Flux causing heating
IN – Ampere turns of the coil
Zm – Magnetic resistance of the "active zone"
Rm – Magnetic resistance of **return path**, i.e. space inside the coil

Magnetic core reduces Rm by permeability times and for an ideal core Rm => 0.
Then **Φ = IN / Zm**



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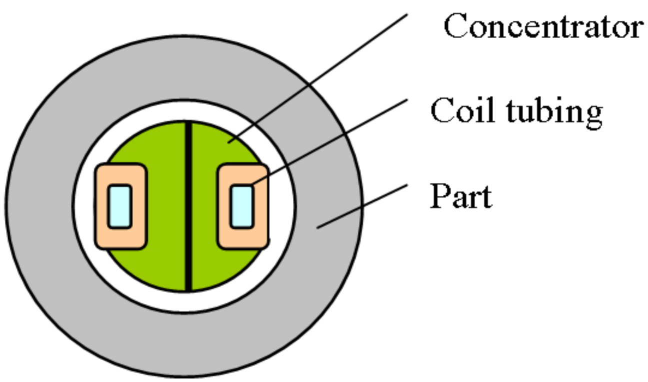
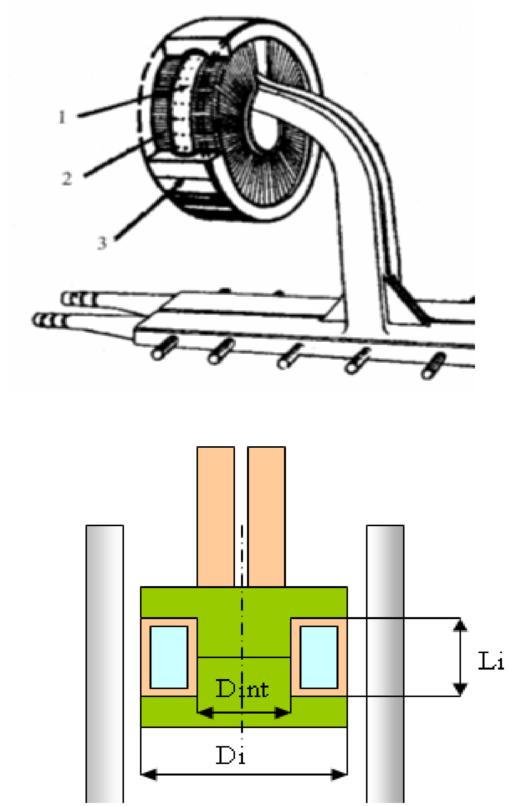
ID Coils with Magnetic Cores

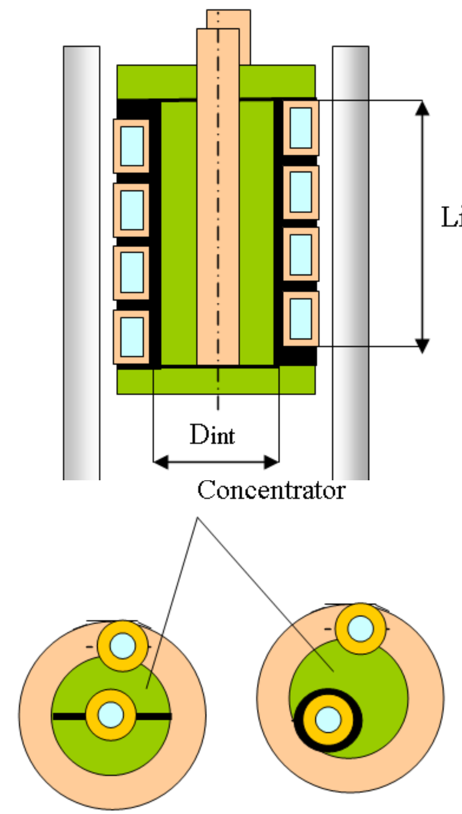
Hair-pin Coil



Single-Turn Cylindrical

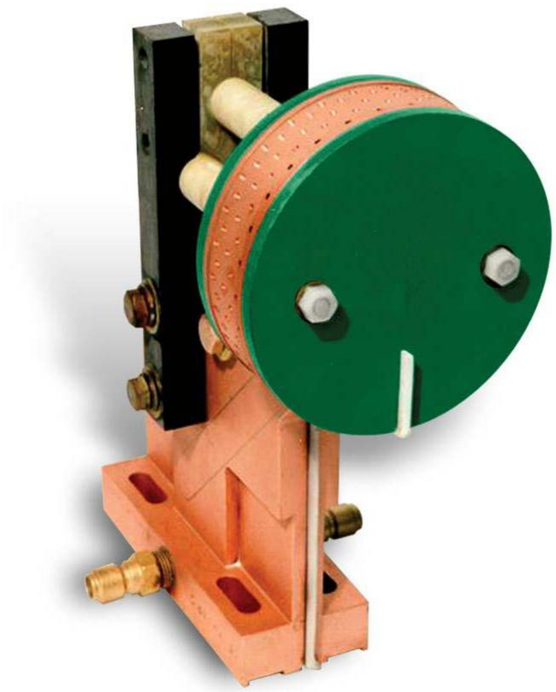


Multi-Turn Cylindrical



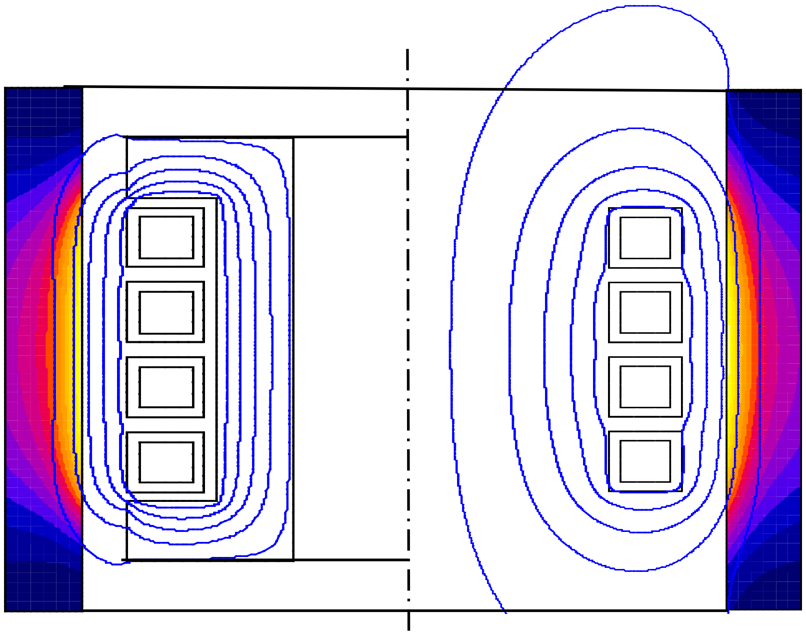
Improvements Expected for I.D. Coils

- 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

Influence of Magnetic Core on ID Coil Parameters



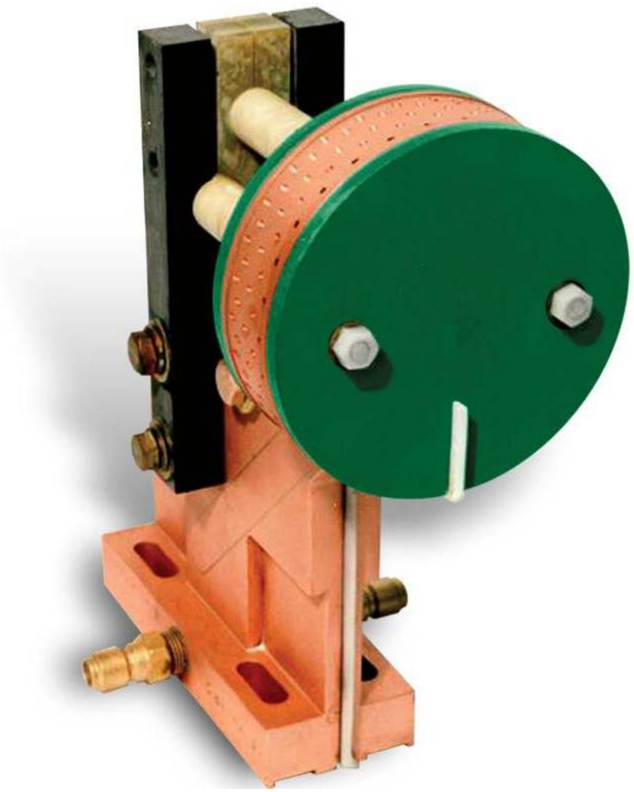
Coil head parameters

Core	Ui, V	Ii, A	Pi, kW	Eff-cy	Coil kVA
Yes	46	875	12.0	84	40
No	44	1850	14.3	70	81

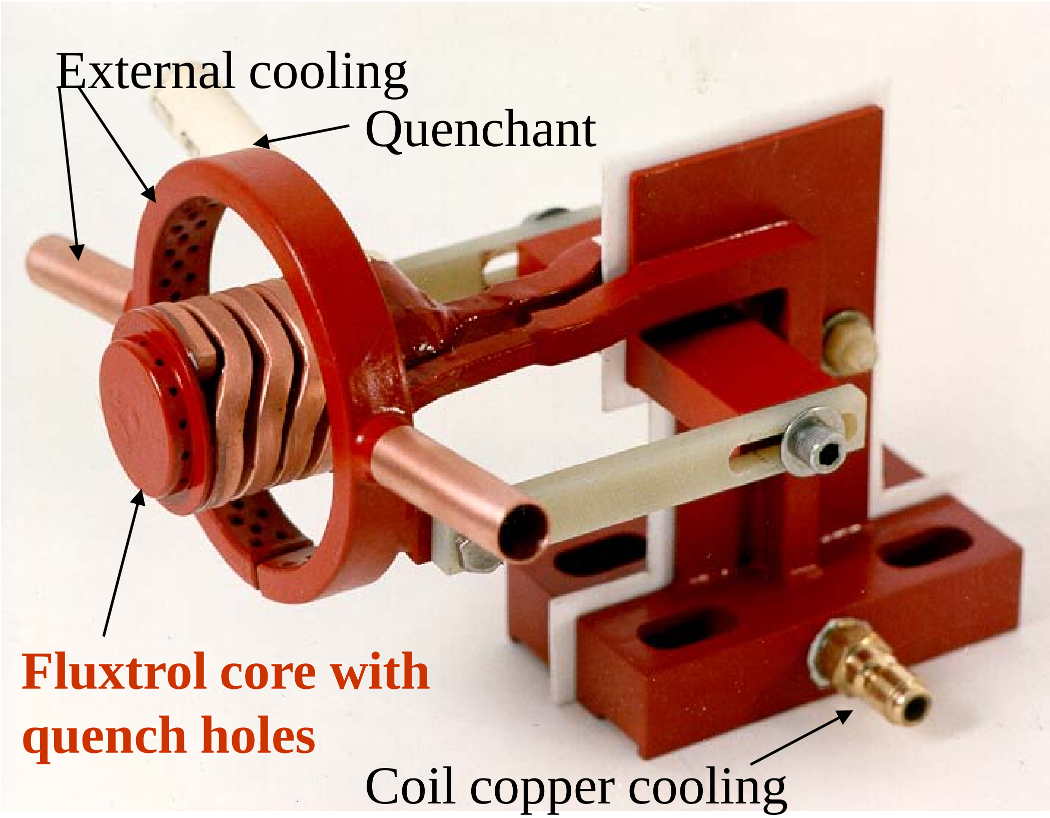
Magnetic field lines and temperature maps for the coils with and without magnetic core (right)

Account for losses and reactive power in the coil leads and supplying circuit shows additional benefits of the core

Examples of Optimized ID Coils



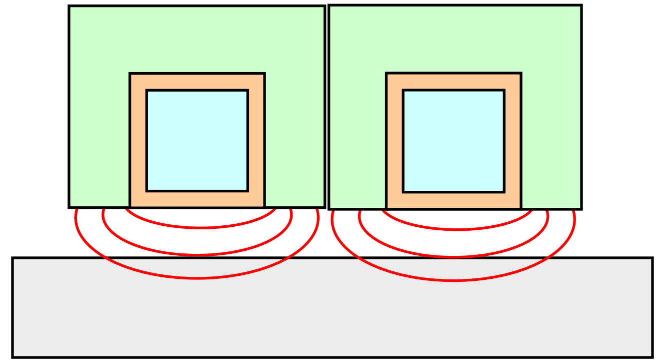
Single turn ID inductor with Fluxtrol A core

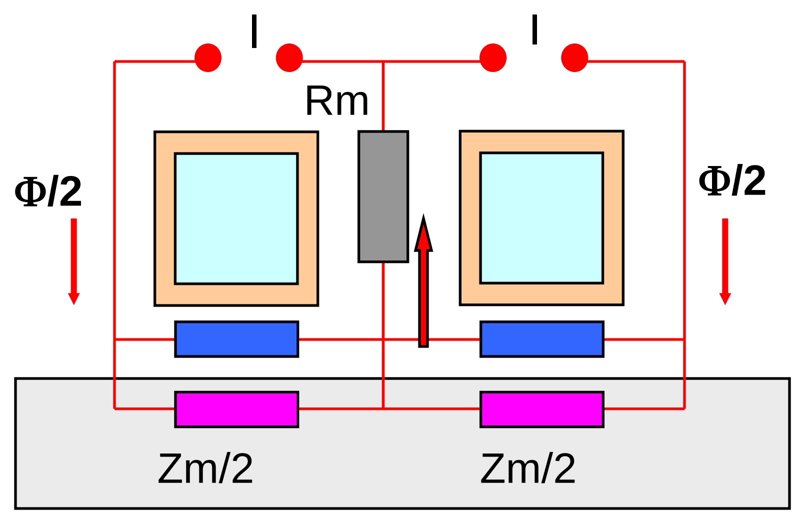


4-turn ID inductor with Fluxtrol 50 core

Effects of Magnetic Flux Controller on Hairpin Coils

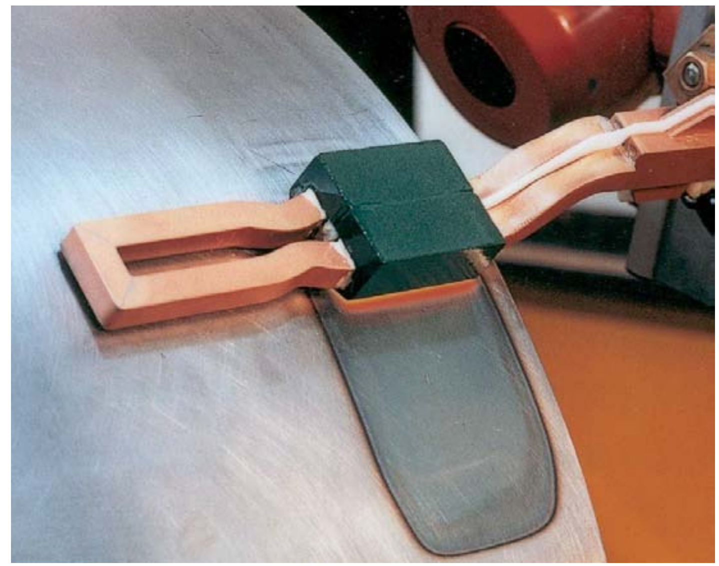
- Magnetic resistance of the back path is mainly due to limited space between the coil legs
- Central pole is critical; side poles are less important though they further reduce current demand
- Application of MFC to a part of the coil provides strong control of power distribution in the part along the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





Improvements Expected for Hairpin and Transverse Flux Coils

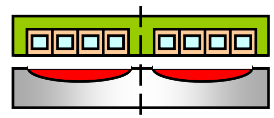
- Shorter heating times
- Substantial energy savings
- Greatly improved heat pattern control
- Drastically reduced current demand
- Reduced losses in power supplying circuitry
- Transverse flux heating - possibility to provide uniform heating in the edge areas

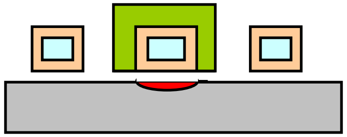


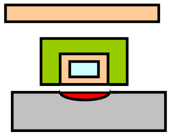
Example of concentrator influence when applied to hair-pin coil (see details on next slide)

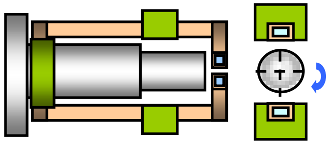
Other Coil Styles Where Concentrators Improve Performance Dramatically

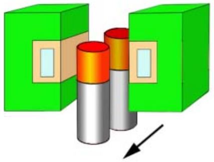
- **Pancake Coil**
- **Split-n-Return**
- **Vertical Loop**
- **Single-Shot**
- **Channel Coils**
- **Transverse Flux Heating Coils**
- Any coil where there is limited space for back path flow of magnetic flux

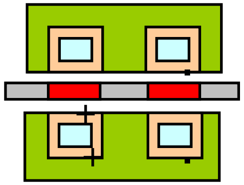












Considerations for Magnetic Controller Material Selection

Electromagnetic characteristics:

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

Thermal characteristics:

- Thermal conductivity
- Temperature resistance

Mechanical characteristics:

- Mechanical strength
- Hardness
- Machinability
- Conformable

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
- Come in either solid, machinable type (Fluxtrol or Ferrotron) or formable type (Alphaform)
- Fluxtrol and Ferrotron MDMs 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

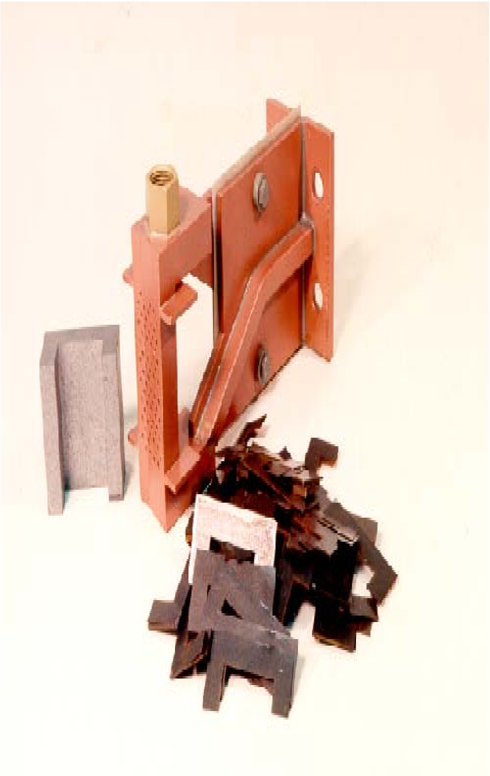
Ferrites

- 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
  - Coil made from Formed Tubing (Alphaform) or Machined Copper (Fluxtrol or Ferrotron)
- Magnetic properties of material
- Frequency, power and duty cycle
- Lifetime of inductor
- Time to get material
- Time to manufacture coil
- Ability to reproduce coil easily



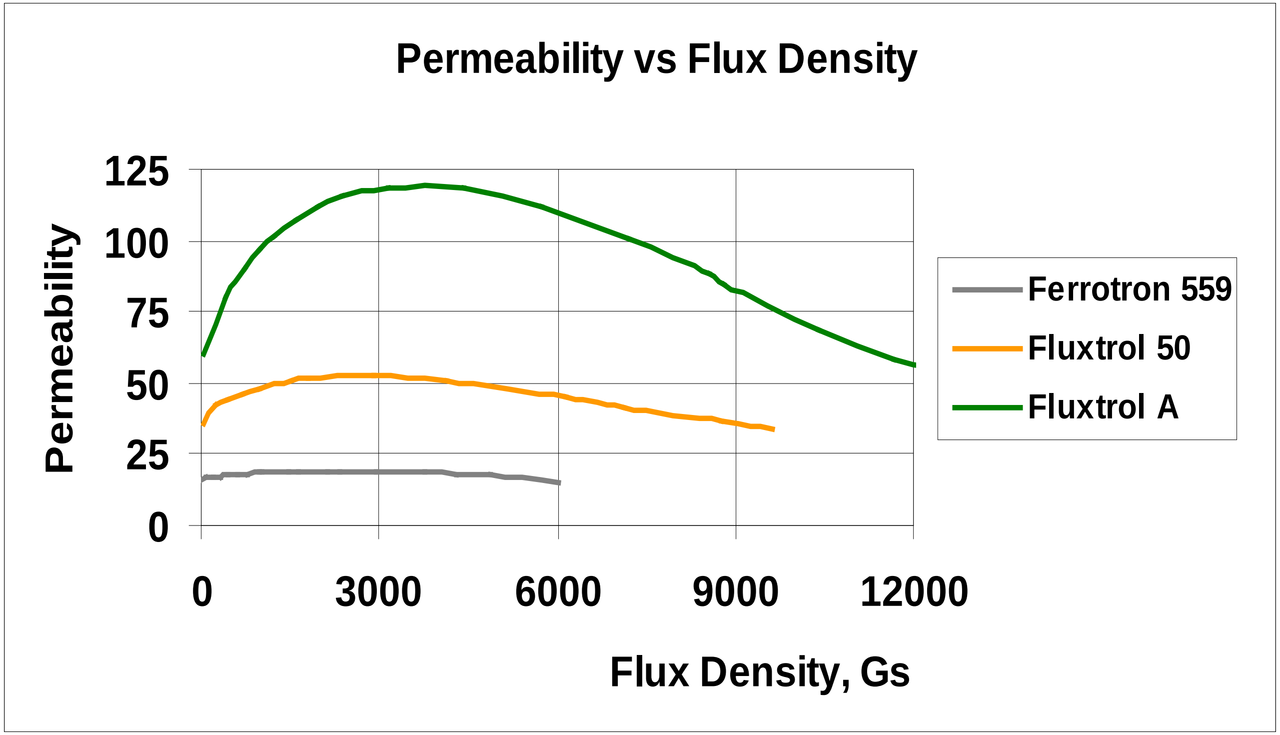
Vertical Loop induction coil with a pile of laminations and Fluxtrol block

Fluxtrol Machinable Products

Properties	Units	Fluxtrol A	Fluxtrol 50	Ferrotron 559H
Product Identification Color		Green	Yellow	Grey
Density ± 2%	g/cm3	6.6	6.1	5.9
Operating Frequency Range	kHz	1–50	10–1000	10–3000
Major Frequency Area	kHz	3–30	50–500	50–1000
Initial Permeability	None	63	36	16
Maximum Permeability	None	120	55	19
Saturation Flux Density	Tesla	1.6	1.5	1.0
Temperature Resistance	Centigrade	250 Long Term 300 Short Term	250 Long Term 300 Short Term	250 Long Term 300 Short Term
Resistivity	kOhmcm	0.5	0.5	>15

- All materials have excellent machinability
- Can work in three-dimensional magnetic fields
- Frequency ranges and resistivity values are only for reference
- Ideal Solution for Machined coils, or coils with rectangular tubing

Magnetic Permeability of Fluxtrol Products



Materials are quasi-linear especially Ferrotron 559

Fluxtrol A material supports permeability above 50 at flux density up to 14000 Gs

Permeabilities don’t drop with frequency:

Fluxtrol A up to 70 kHz; Fluxtrol 50 up to 500 kHz; Ferrotron 559 up to 15000 kHz

Standard C-shaped Concentrators

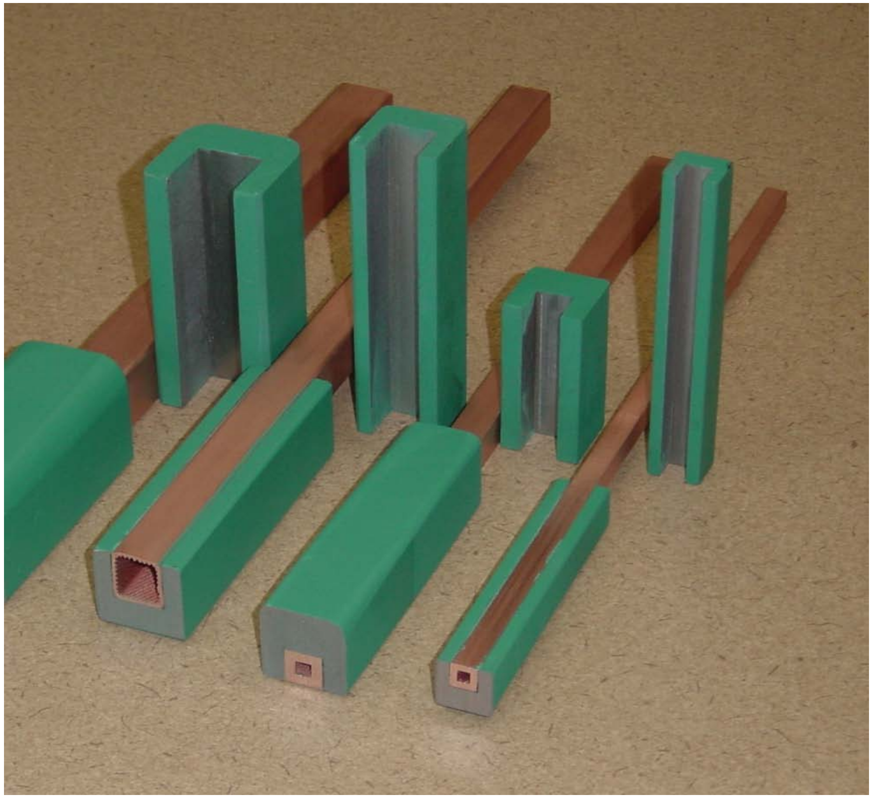
Besides of round and rectangular shapes, standard C-shaped concentrators are available

They are made of Fluxtrol LRM of two types: LRM LF and LRM HF

C-shape concentrators have optimal material orientation and dimensions that fit majority of standard tube sizes.

They may be used at low frequencies instead of laminations or at high frequencies where concentrators are not used at all.

Examples of LRM concentrators



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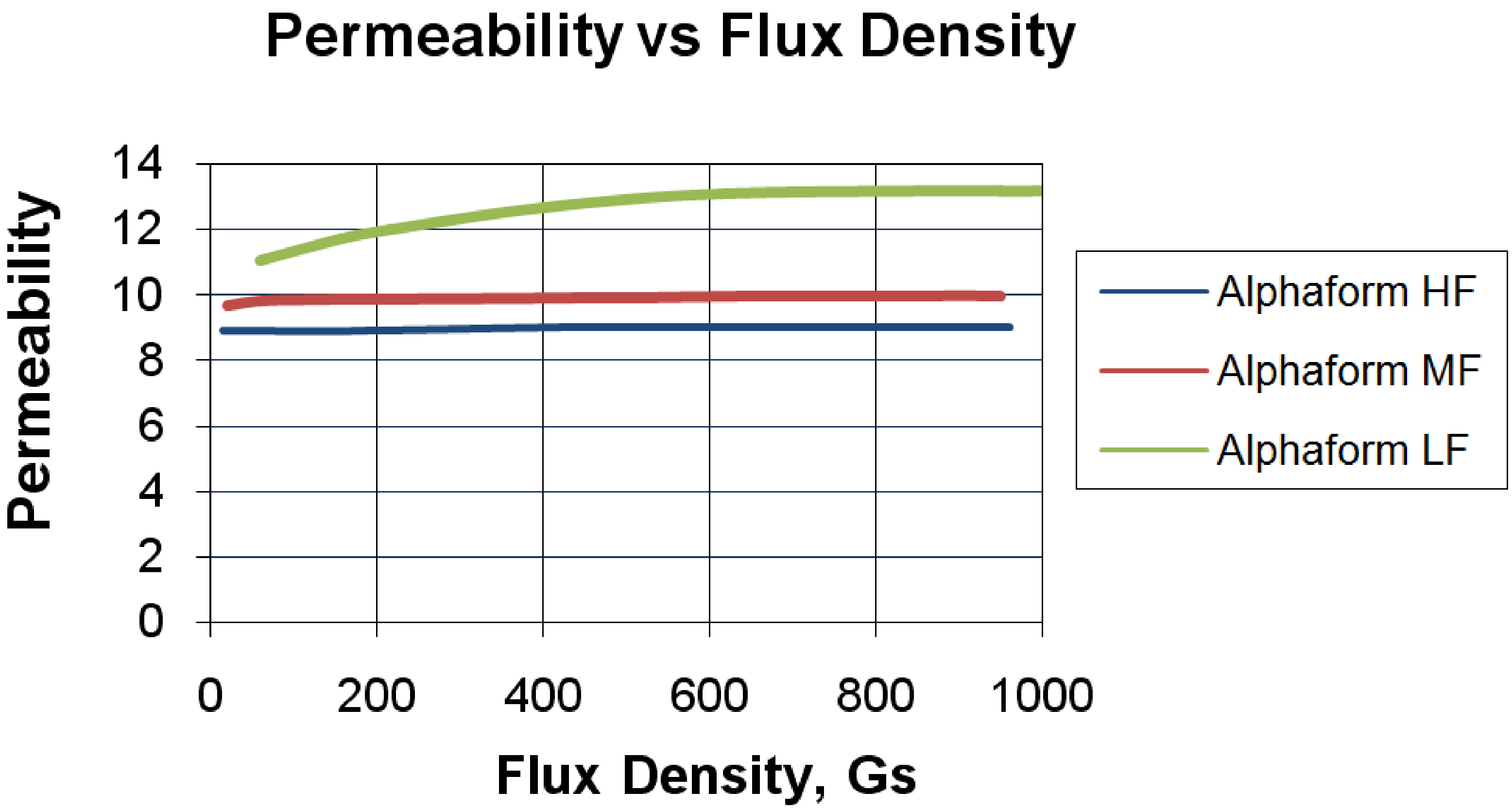
Alphaform Formable Products

- Alphaform materials are formable magnetic flux controllers. Alphaform comes in 3 grades designed for use at different frequencies: LF (1-80 kHz), MF (10 - 450 kHz) and HF (20 - 3000 kHz). These materials are a good alternative to the traditional machinable Fluxtrol and Ferrotron materials for complex shaped induction coils manufactured with formed tubing. In these applications, the Alphaform adheres to the contours of the induction coil to ensure good heat transfer between the concentrator and the water cooled copper.

Alphaform applied to an ID Coil

Magnetic Permeability of Alphaform Products



Applying Alphaform Products

- Applying Alphaform to an induction coil is a relatively simple, 3 step process. The first step is to conform the material to the areas of the induction coil you desire to enhance the heating of. The next step is to constrain the material so that it will maintain it's shape through the curing process. The final operation is to bake the material in the oven to cure the material to finalize the geometry. After curing, the Alphaform is no longer formable and is a mechanically strong material, much like our machinable products.

Permeability Influence

Workpiece:

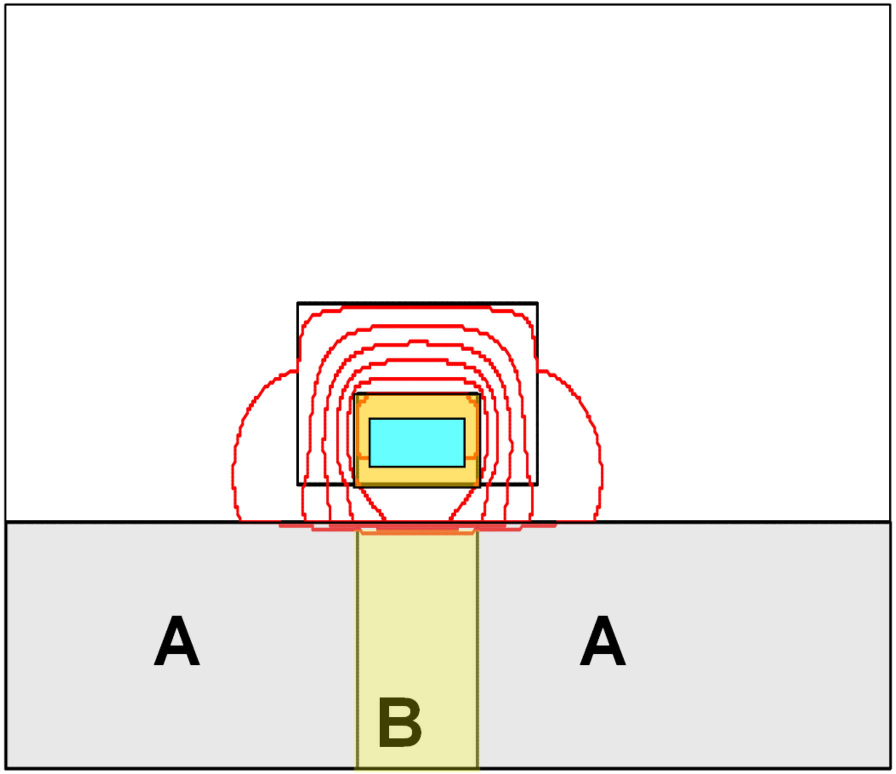
- Flat body composed of a central part B and two side areas
- Materials – magnetic or non-magnetic steel

Conditions:

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

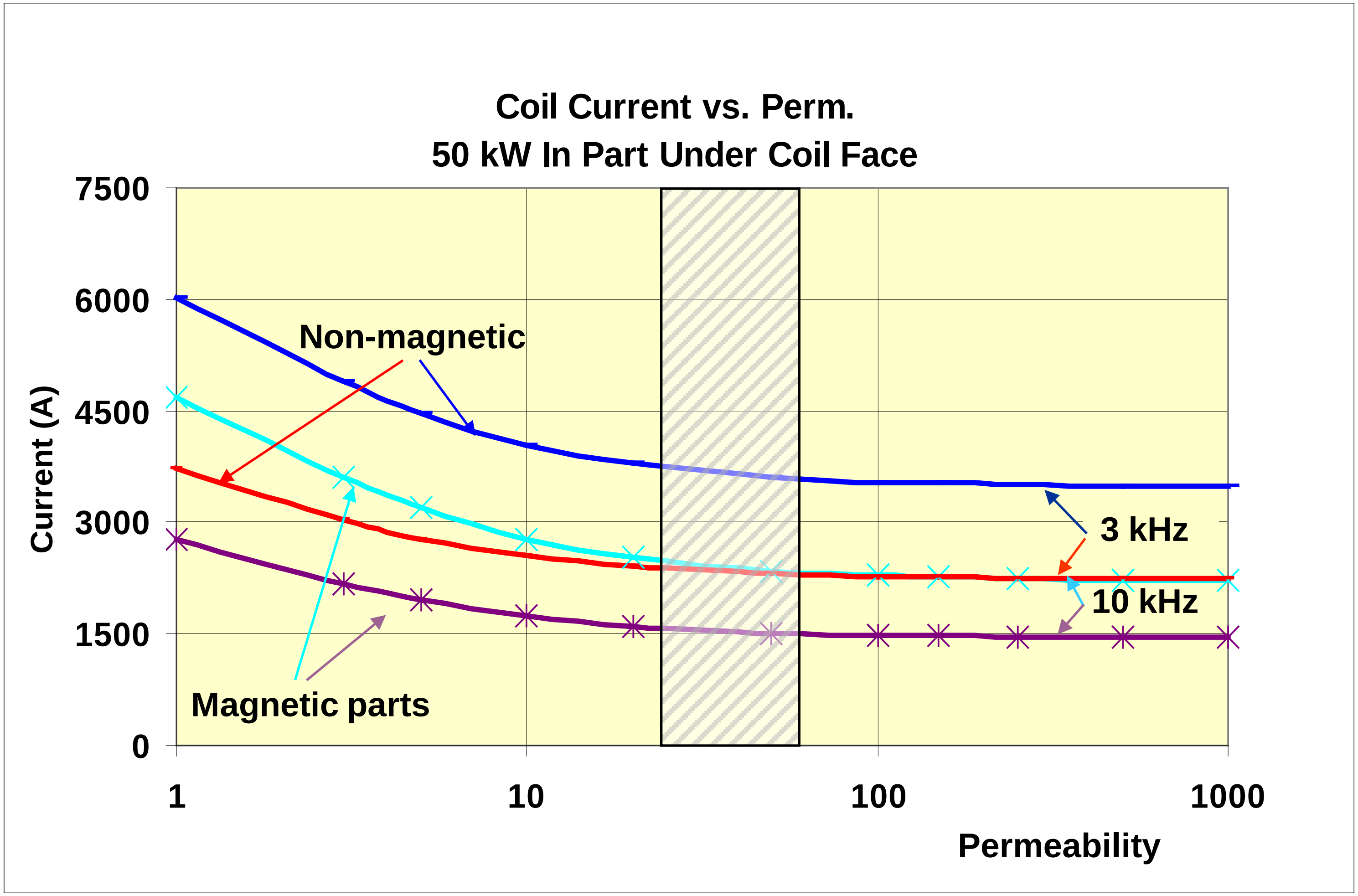
Considered parameters:

1. Current demand
2. Power demand

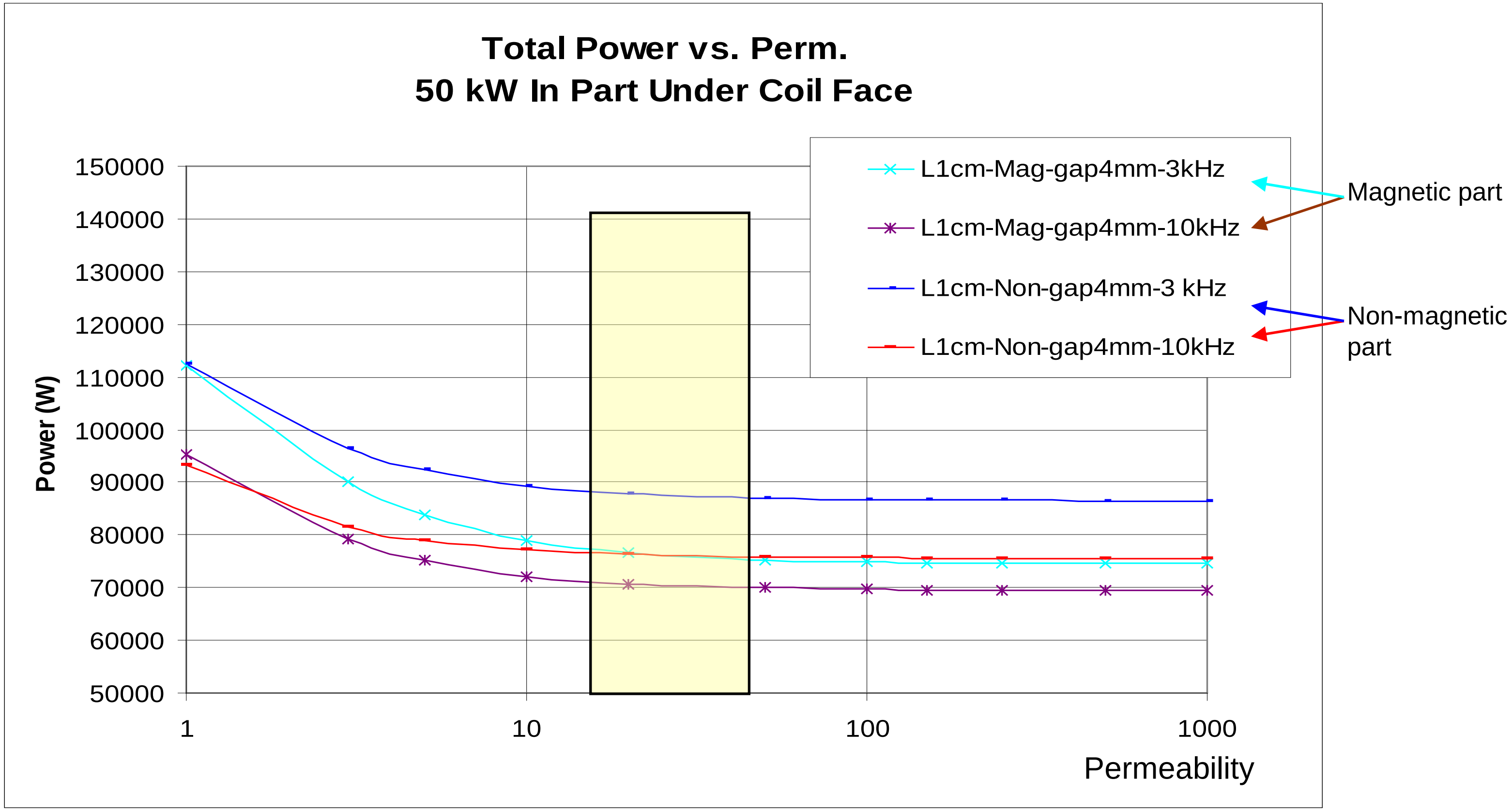


A – side areas, **B** – work area
Gap 4 mm; Coil face width 19 mm
Frequencies 3 and 10 kHz

Coil Current Demand versus Concentrator Permeability



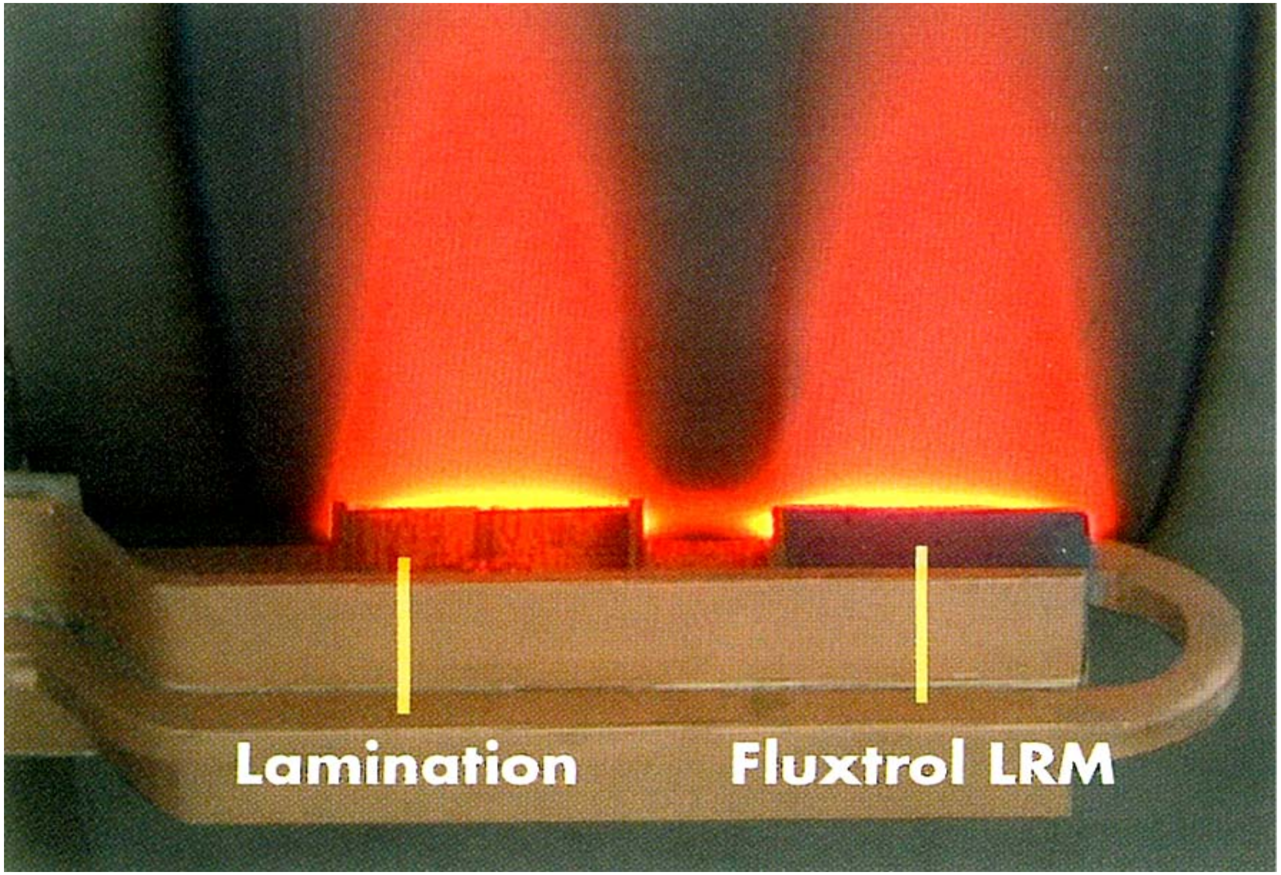
Results: Total Power vs. Permeability



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

Notice: no improvement at higher permeability for all studied cases

Performance of Fluxtrol vs. Lams

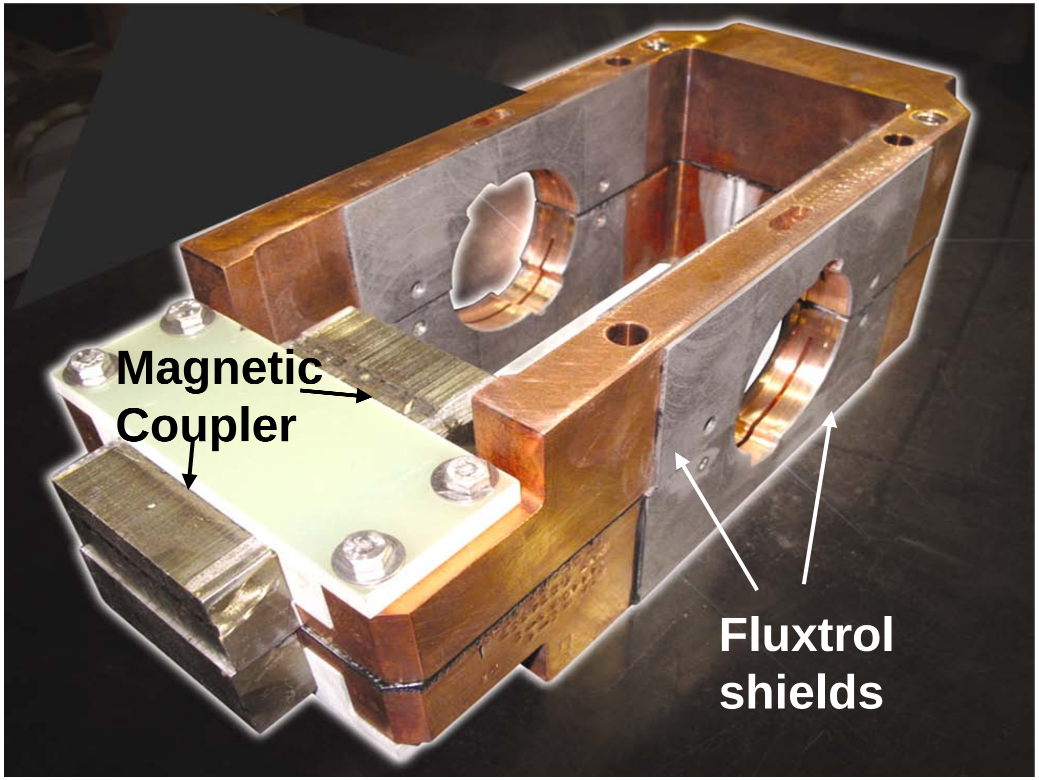


Fluxtrol LRM provides the same heat pattern on the plate as laminations

Magnetic Control in Crankshaft Hardening

- Crankshaft hardening involves local heating of the bearing and/or fillet region of a crankshaft
- Magnetic controllers should always be used on crankshaft coils for
  - Heat pattern control
    - Shape of Pattern
    - Balance between areas w/wo counterweights
    - Oil hole compensation
  - Efficiency improvement
  - Reduction of part distortion

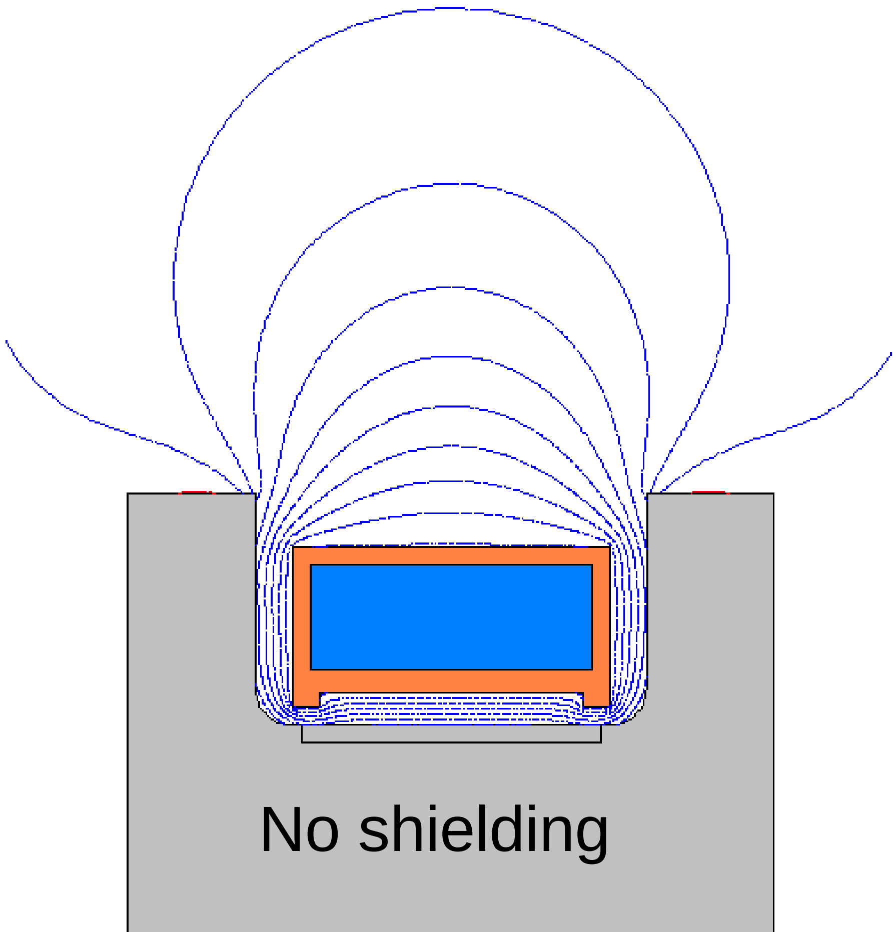
Non-rotational Crankshaft Hardening

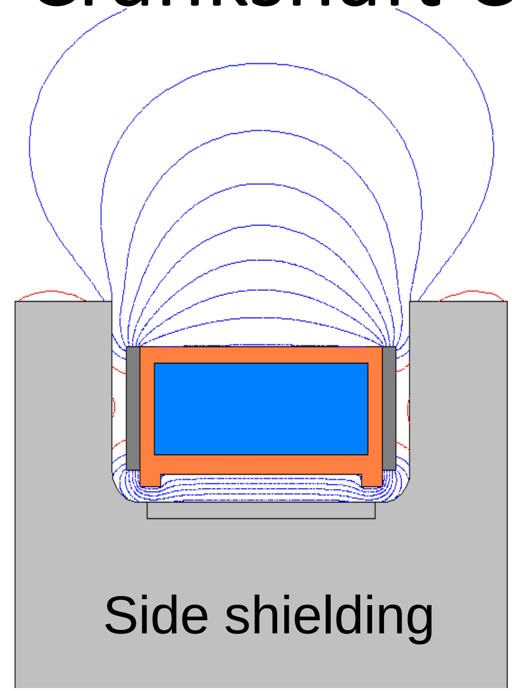


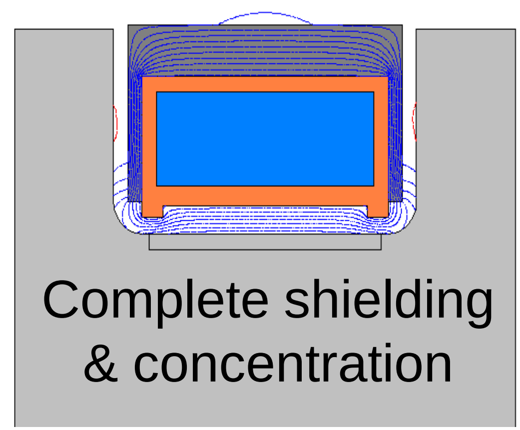
SharP-C inductor with Fluxtrol side shields

courtesy of INDUCTOHEAT Inc.

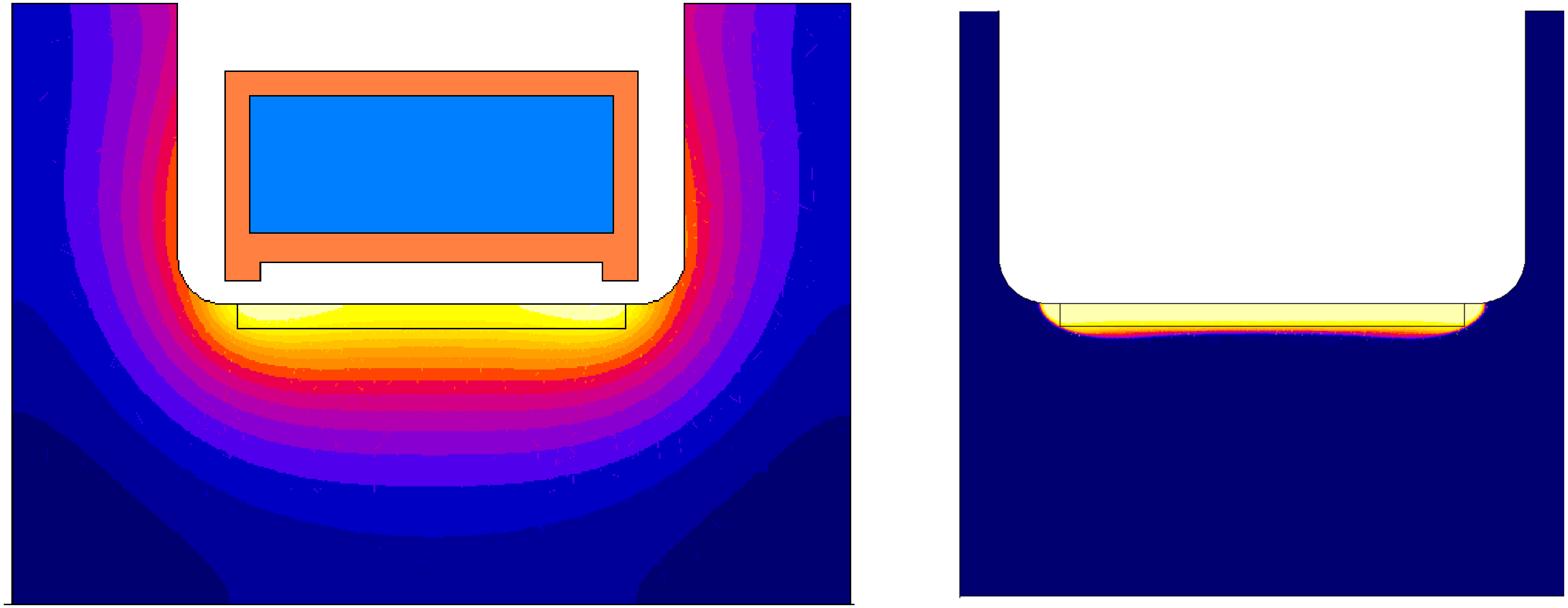
Magnetic Field Shielding of Crankshaft Coil







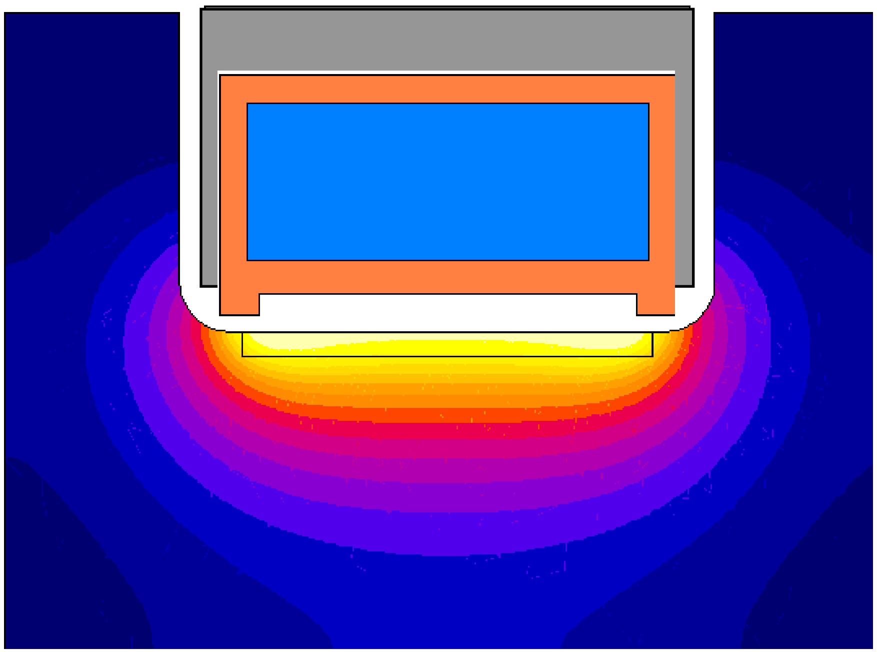
Hardening without magnetic controller

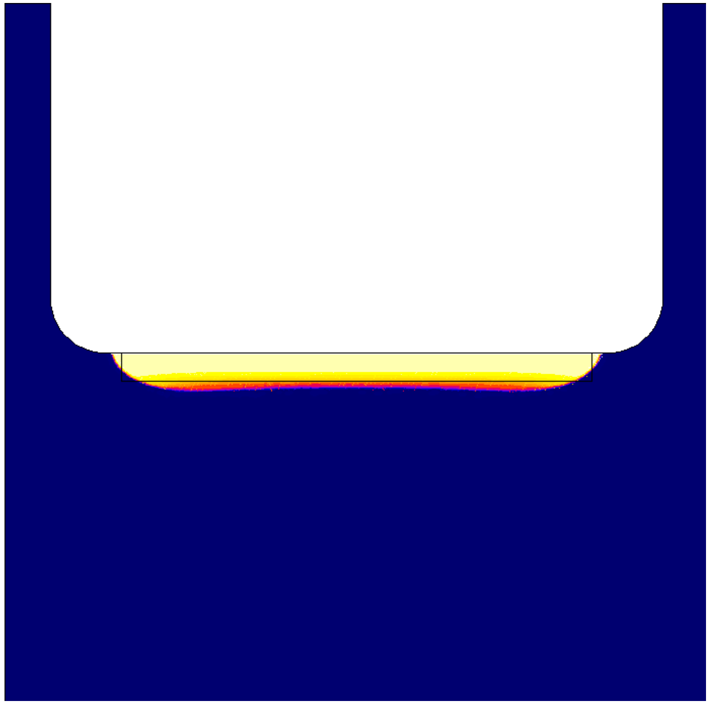


Temperature at the end of heating and martensite % distribution after hardening

Flux 2D program + Metal 7

Hardening with Magnetic Controller





Temperature at the end of heating and martensite % distribution after hardening

Flux 2D program + Metal 7

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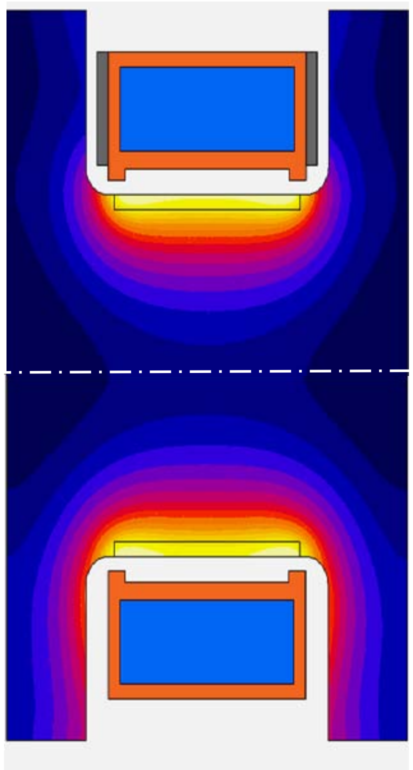
Simulation Results

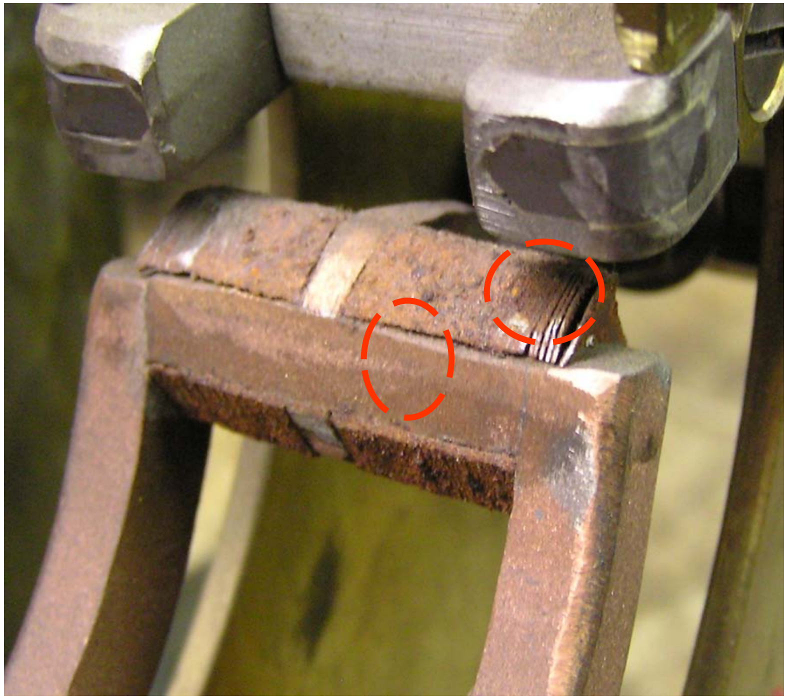


Parameters	No Controller	Side Controllers	C-shaped Controller
Current, A	4.35	4	3.5
Voltage, V	27.6	30.8	31.2
Electrical Efficiency, %	94	93	92.5
Coil Power, kW	67	54.7	51
Coil kVAs	123	123	109

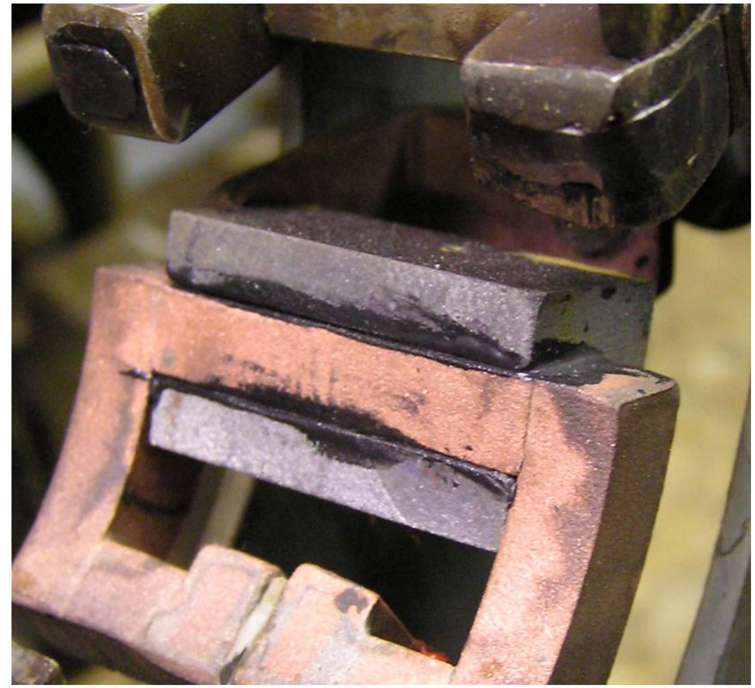
Notes:

- With controller the required power is significantly lower in spite of a formal reduction of electrical efficiency
- For stationary heating the concentrators/shields can compensate influence of the crankshaft throws and webs on hardness pattern

Life Time Increase for U-shaped Coil by Replacing Laminations with Fluxtrol A



Part of U-shaped coil with Laminations

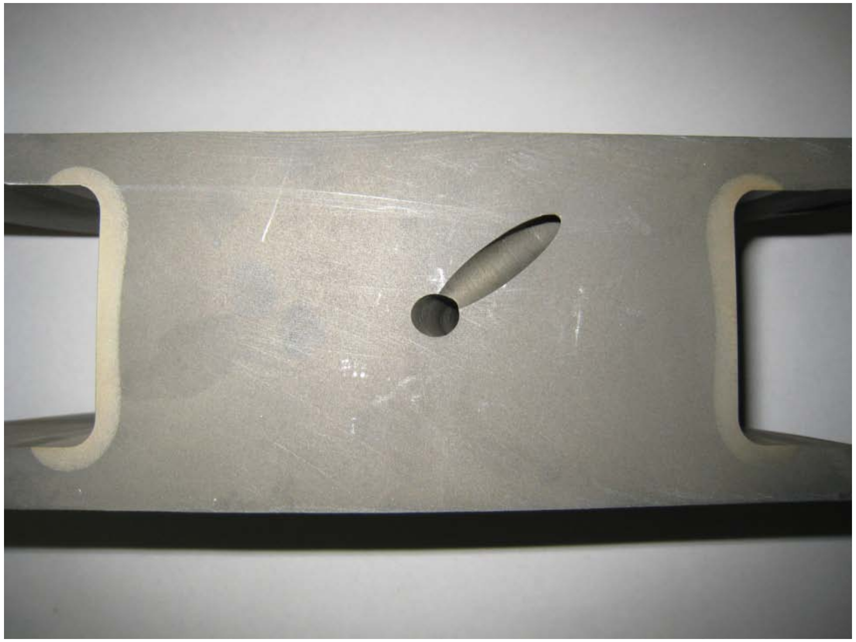


Part of U-shaped coil with Fluxtrol LRM

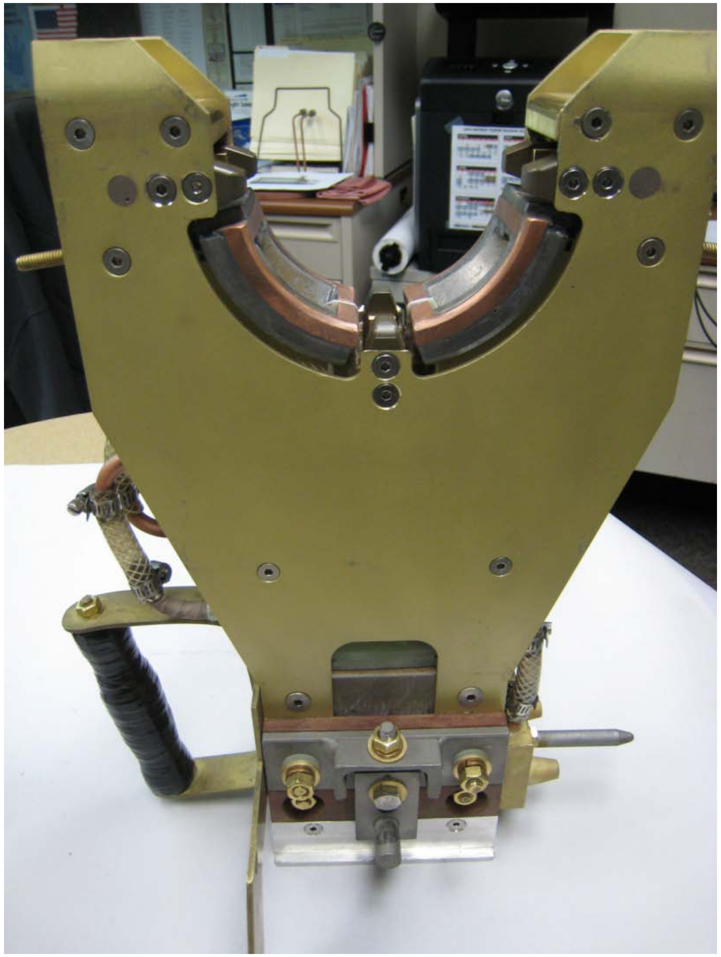
Life time of coils with Fluxtrol LRM is almost doubled

Courtesy of Norton Manufacturing

U-Shaped Coil for Fillet Hardening



12 L Diesel Crankshaft



Conclusions

- Magnetic Flux Controllers are a very important component of the induction heat treating coil design
- Magnetic Flux Controllers have a beneficial effect on many types of inductors
- Fluxtrol, Ferrotron and Alphaform materials work well in induction heat treating applications

More Information

More information about magnetic flux control, controllers and application technique may be found on www.fluxtrol.com

Thank you!