FLUXTROL Inc. Centre for Induction Technology™

Padua, Italy, May 24-27, 2016

HES-16

STRIATION EFFECT IN INDUCTION HEATING: MYTHS AND REALITY

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Layout

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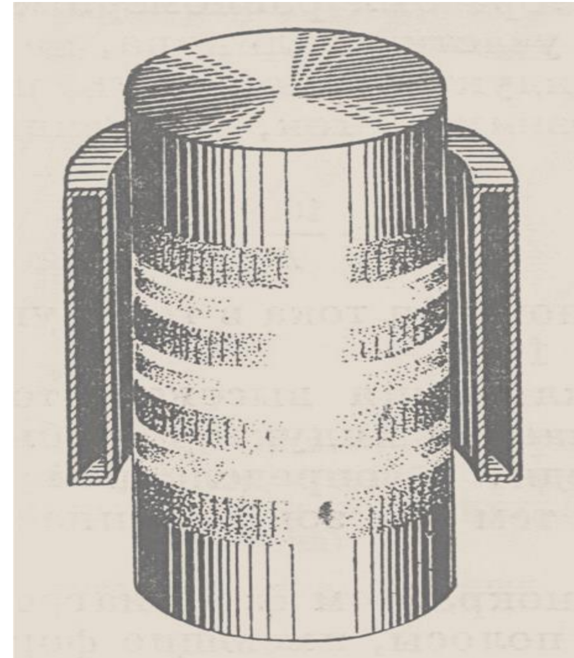
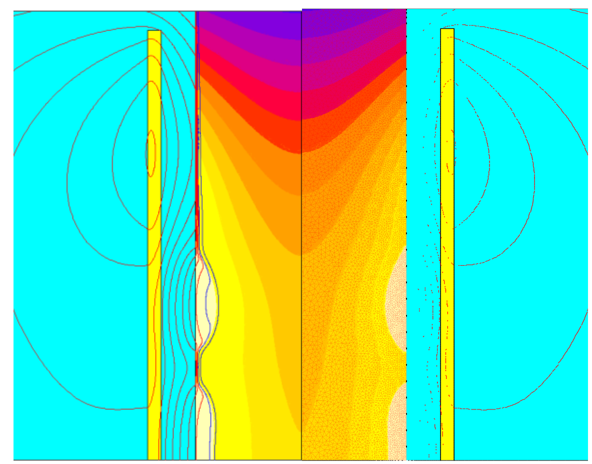
2. History of discovery
3. Early findings and theories
4. Latest findings
5. Present study
6. Magnetic properties of steel vs. temperature
7. Factors that influence zebra effect
8. Dynamics of zebra formation process
9. Newer theory
10. What else?





First Information about Striation Effect

Findings and statements:

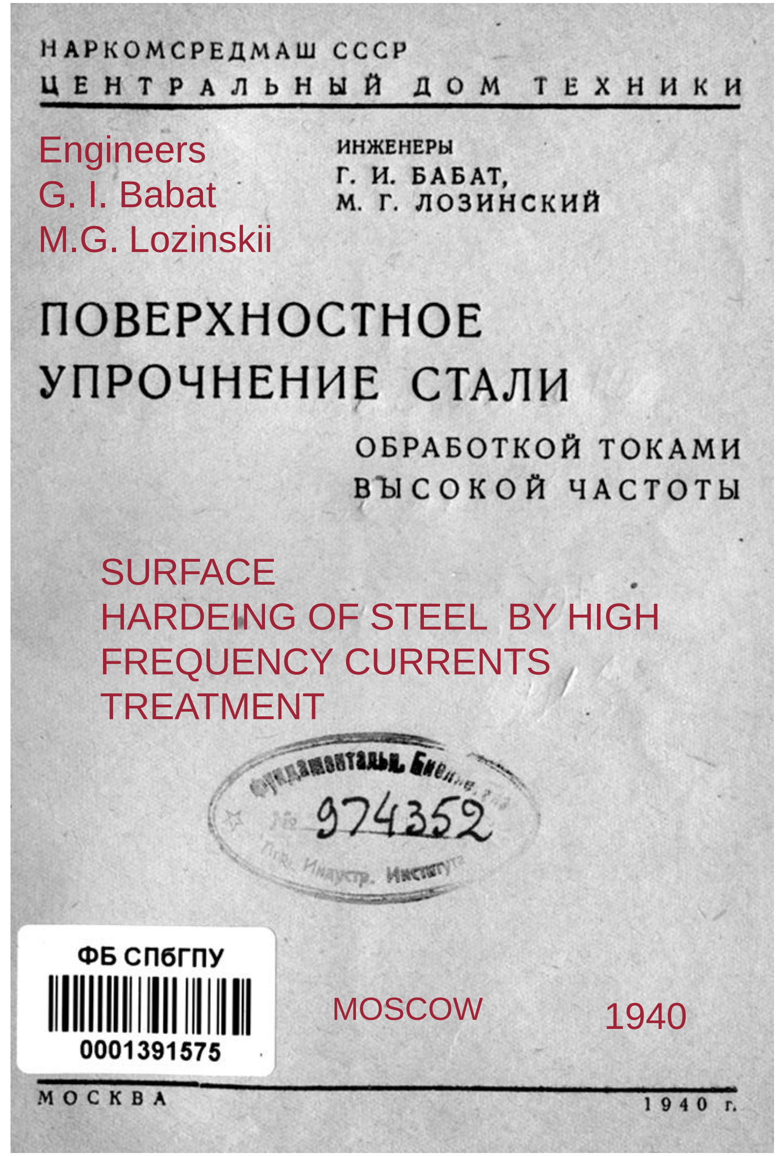
- Temperature "striation" can occur during fast heating of steel parts in non-uniform field, i.e. in multi-turn coil

- Striation happens in an interval 650-750 ^{0}C

-- Cause of striation is natural instability with positive feed back from tiny local "overheating"

- This effect can strongly influence the coil design and even ability to harden uniformly the part length exceeding several "hot reference depths"

- With incorrect coil design we can obtain the part with separated hardened **strips** and **spots (!)**.



НАРКОМСРЕДМАШ СССР
ЦЕНТРАЛЬНЫЙ ДОМ ТЕХНИКИ

Engineers
G. I. Babat
M.G. Lozinskii

ИНЖЕНЕРЫ
Г. И. БАБАТ,
М. Г. ЛОЗИНСКИЙ

ПОВЕРХНОСТНОЕ УПРОЧНЕНИЕ СТАЛИ
ОБРАБОТКОЙ ТОКАМИ ВЫСОКОЙ ЧАСТОТЫ

SURFACE HARDEING OF STEEL BY HIGH FREQUENCY CURRENTS TREATMENT

MOSCOW 1940

МОСКВА 1940 г.

Further Information

Findings and statements:

-“Zebra” was mentioned the first time

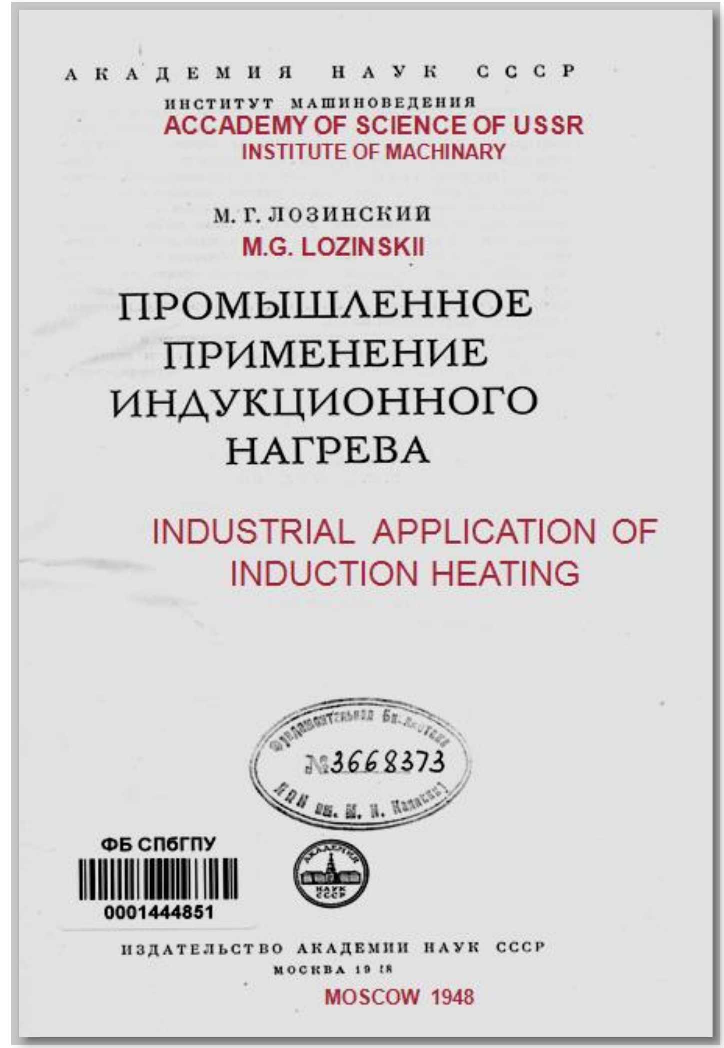
- Multiple studies were performed to “quantify” the results; formulas were proposed for conditions of striation occurrence

- Behavior of Mu vs. temperature near Curie point was considered as an important factor with Armco iron the most favorable for zebra formation

- Zebra effect is still considered as a limiting factor in surface hardening (under certain conditions)

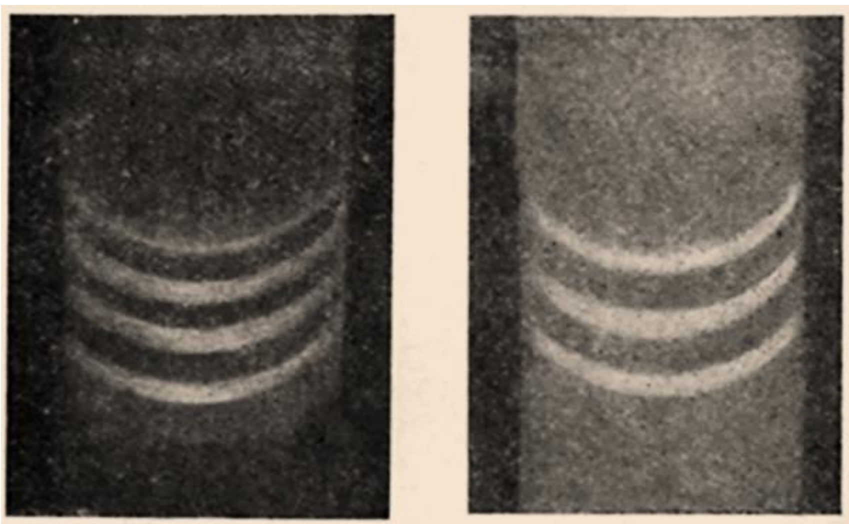
Possible cause of striation: MECHANICAL STANDING WAVES due to magnetostriction, influencing resistivity of material in the nodes (!).

No information about zebra effect was found later until recently…..

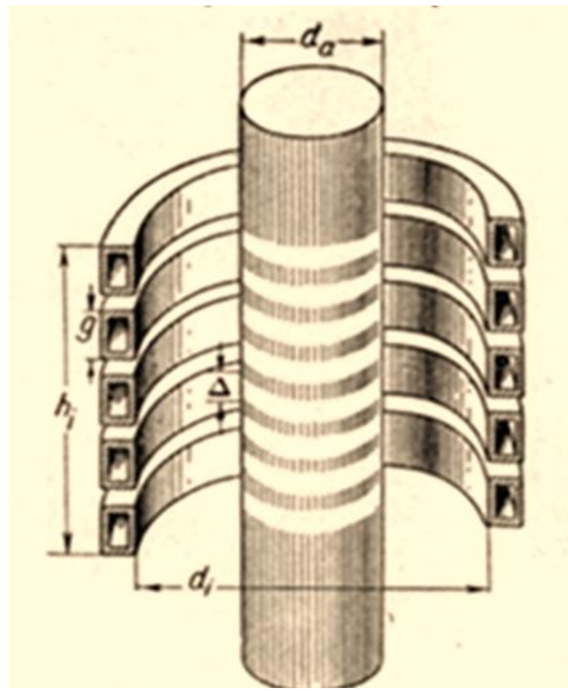


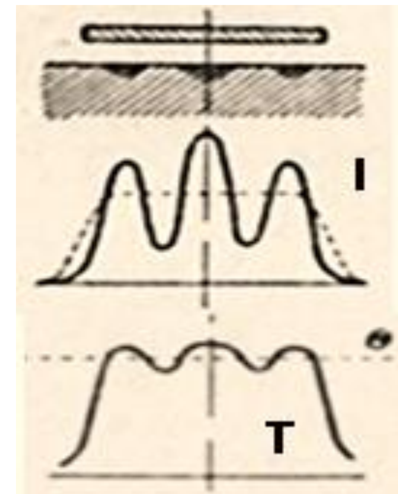
Upgraded version of this book was published in English by Pergamon Press, Oxford, in 1969, i.e. 20 years later!

Photos and Pictures



M. Divilkovsky, f= 477 kHz (left) and 242 kHz (right). Armco iron

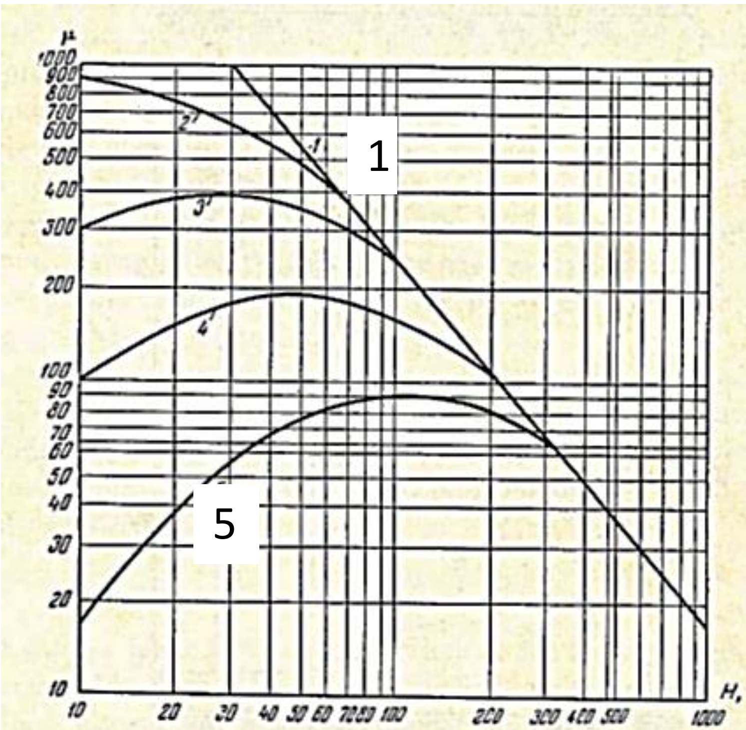




G.I. Babat, Induction Heating of Metals and its Industrial Applications. 2nd edition, Energia, 1965, 552 p.

Industrial applications of induction heating

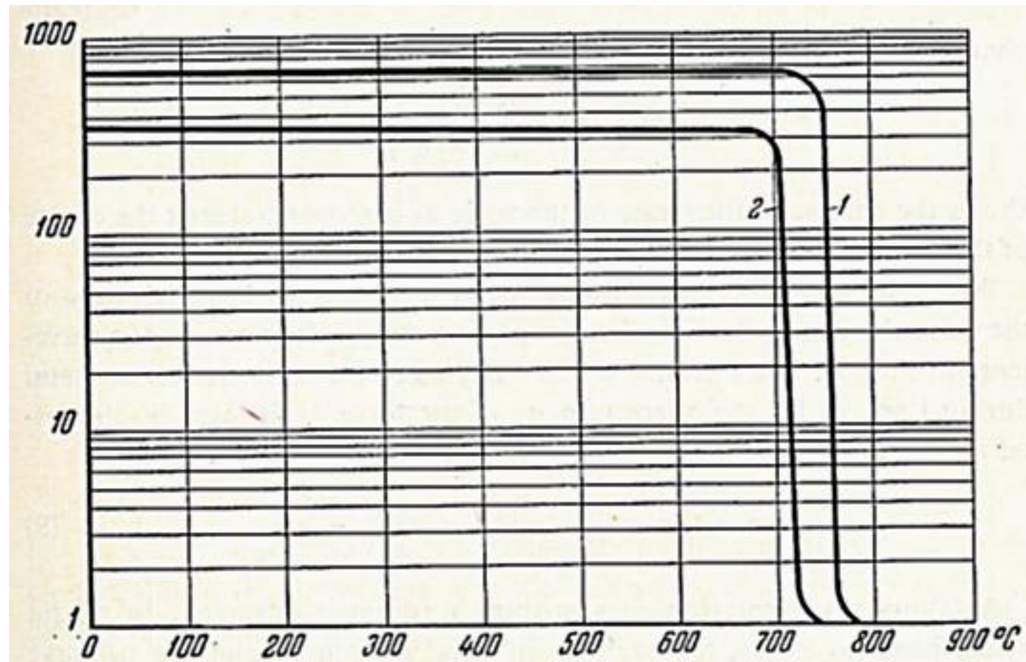
Lozinskii M.G.(1969). Pergamon Press, Oxford, 672 p.



Mu versus H for carbon steels

1 – pure iron

5 – eutectoid steel

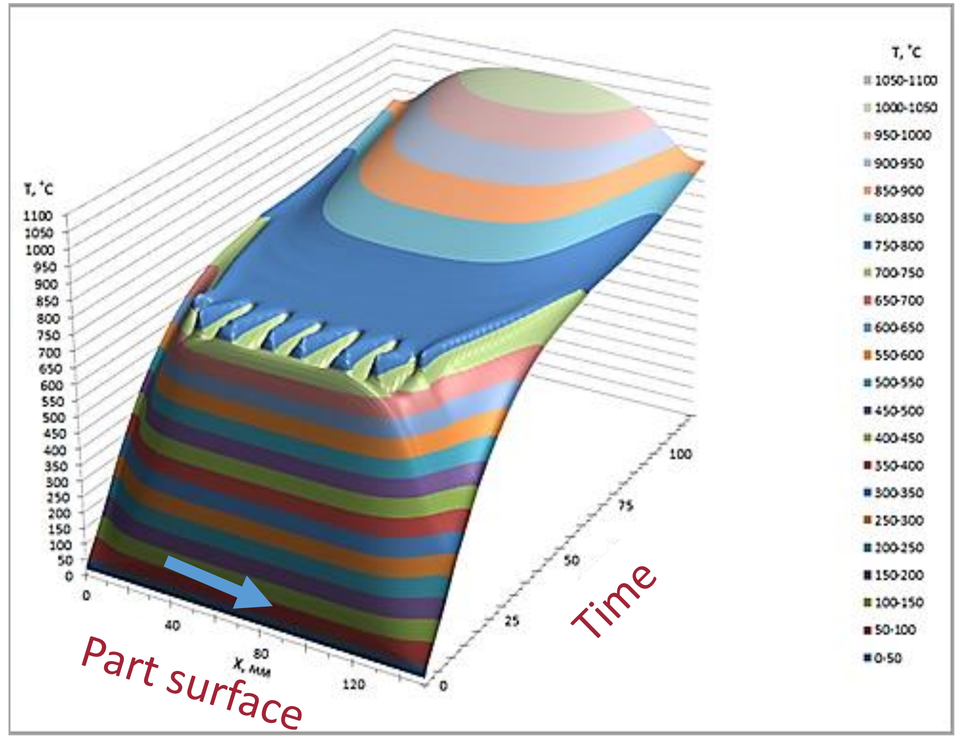


Mu versus T for pure iron (1) and carbon steel (2)

Recent Findings

Findings and statements:

- Experimental proof of striation effect in static and scanning processes
- Possibility to simulate striation effect
- Finding that a "speed" of permeability decrease near Curie point is a leading factor causing zebra effect
- Influence of zebra effect on the coil parameters and power source performance was shortly considered
- Cause of striation: instability of permeability near Curie point.
- Andronov-Hopf bifurcation phenomenon was proposed for description of temperature oscillation.



Source: S.V. Dzliev et al., Instability in induction heating of magnetic steel. J. of Induction Heating, no. 23, 2013, in Russian

Factors that Influence Zebra Effect

Induction system:

Geometry – flat or cylindrical

Coil diameter, length and design (multiturn, impermeable sheet, Litz layer)

Part diameter and length

Magnetic and thermal properties of the part

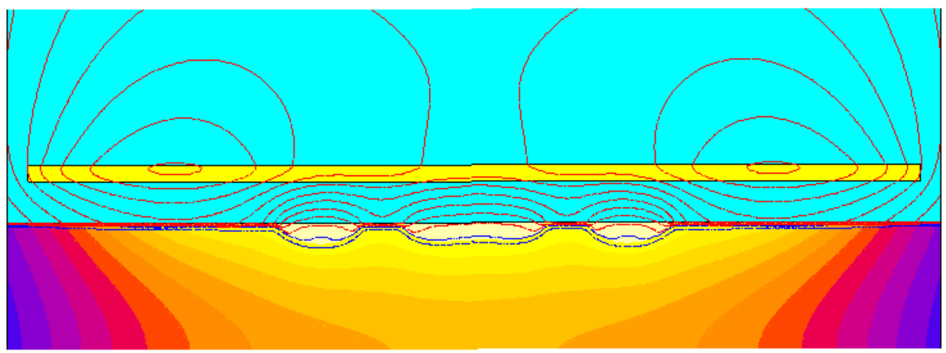
Regime: static or scanning

Signal: frequency, current, voltage or power supply

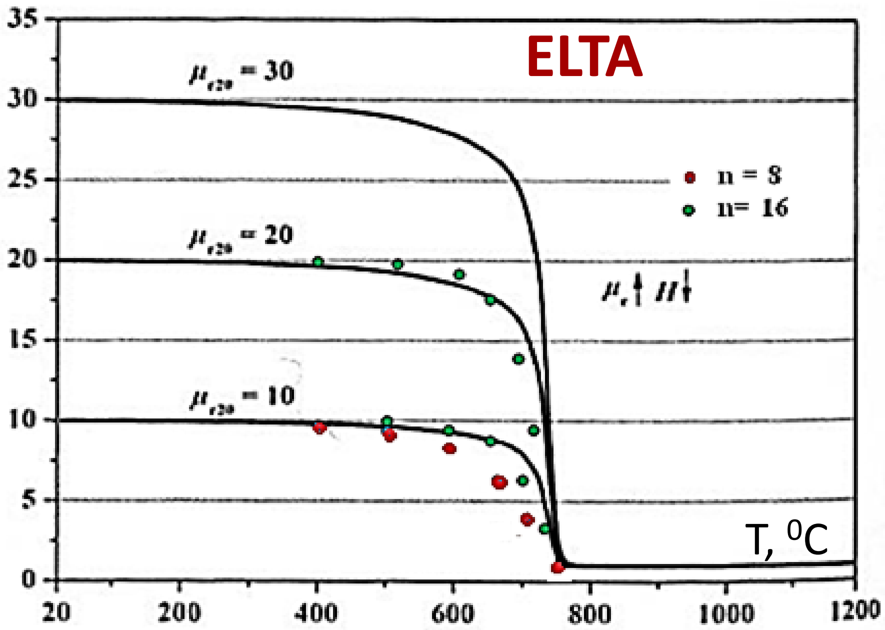
Present study:

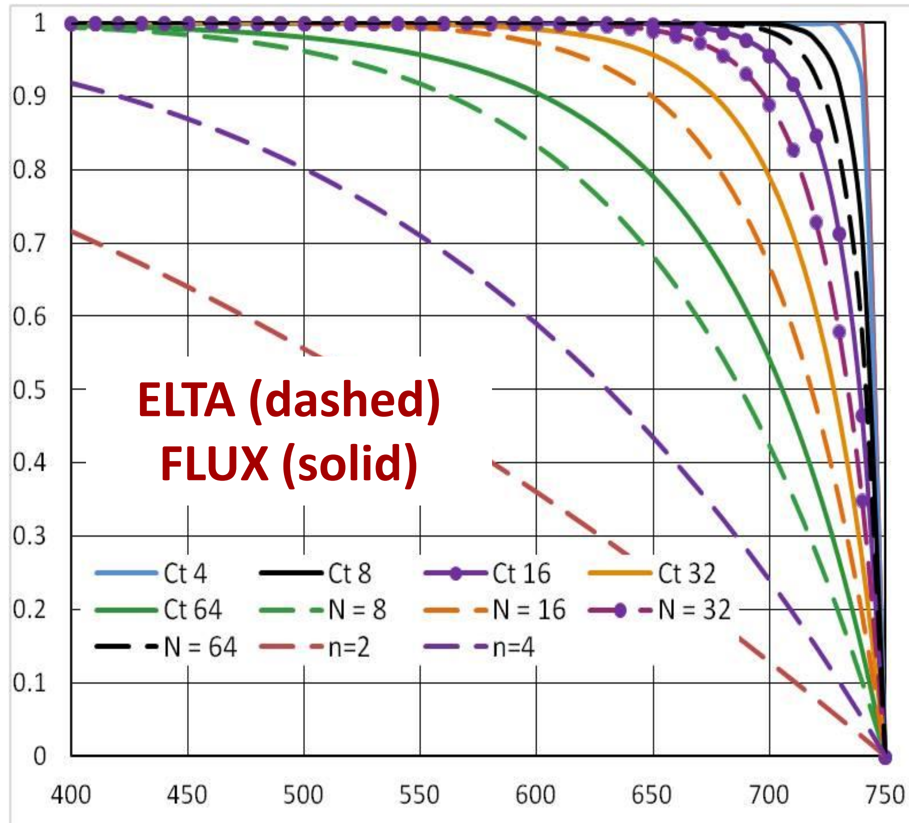
- Influence of permeability behavior
- Coil type (Litz or solid sheet)
- Influence of frequency and power
- Dynamics of phenomenon
- Physics of phenomenon

Flux 2D/3D program was used in our study



Mu versus Temperature in Elta and Flux



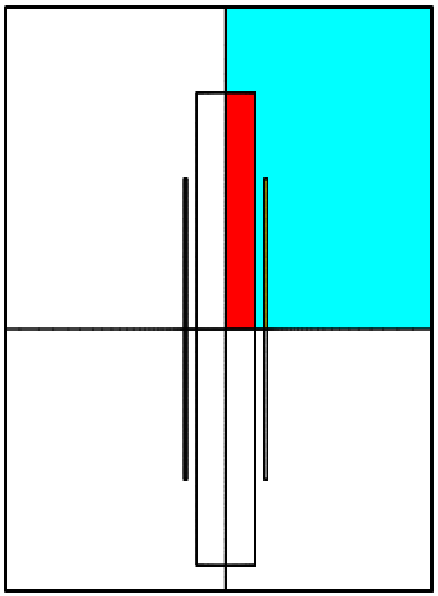


$$\mu(T) = 1 + (\mu - 1)\left(1 - \left({}^{T}/_{T_k}\right)^{n}\right)$$

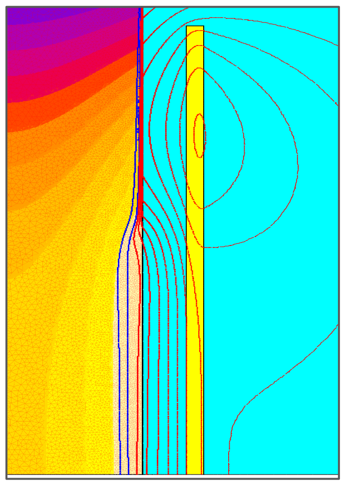
$$B(H) = \mu_0 H + J_s \frac{H_a + 1 - \sqrt{(H_a + 1)^2 - 4H_a(1-a)}}{2(1-a)}$$

$$\mu(T,H) = \mu(H)K(T);\ K(T) = \left(1 - \exp\left(\frac{T - Tc}{Ct}\right)\right)$$

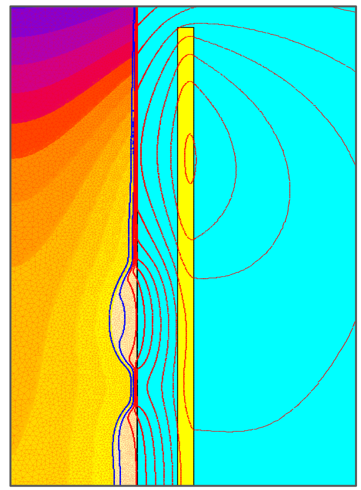
Color Maps of Temperature and Magnetic Lines for Different Cts



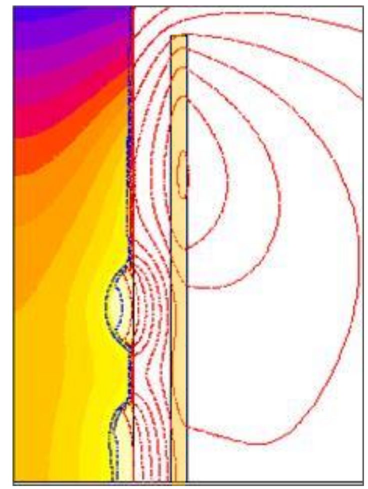
Geometry:
Long part and Litz coil



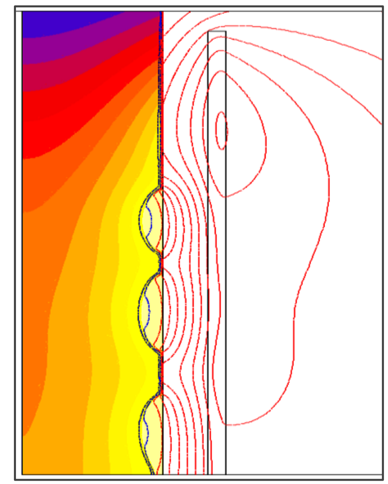
Ct = 64



Ct = 32 (N = 20)



Ct = 16

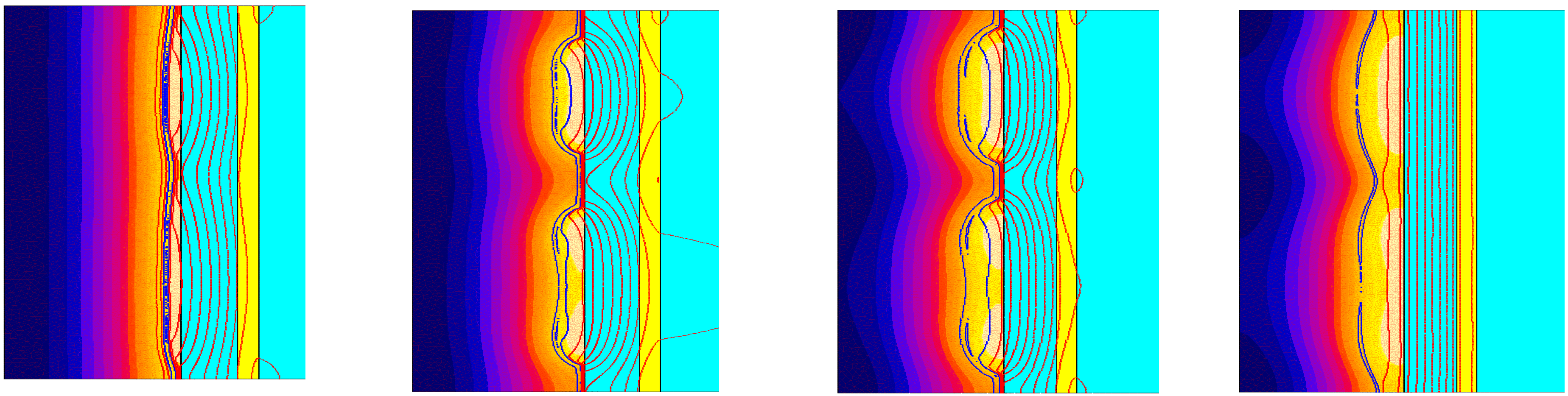


Ct = 16
40 kHz
16 sec

f = 20 kHz, time 22 sec.
Litz coil, I = 2000 A

Dynamics of Zebra Effect

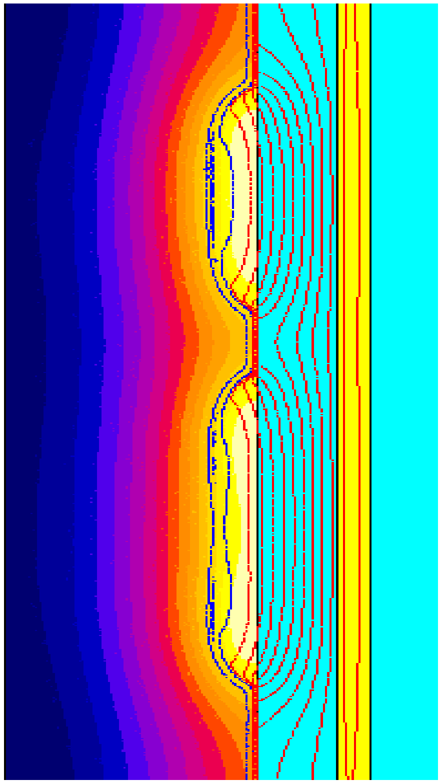
Piece of infinitely long system is considered in further study

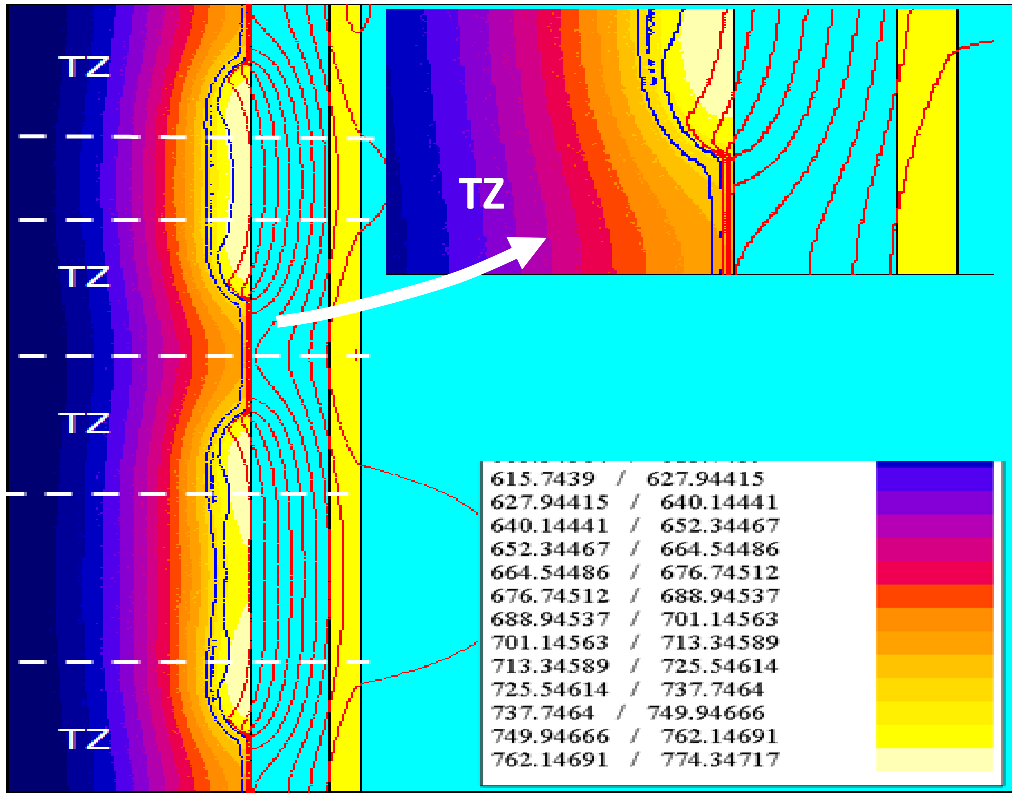


Time: 16 sec 20 sec 24 sec 28 sec

Litz coil, frequency 20 kHz, I = 3000 A

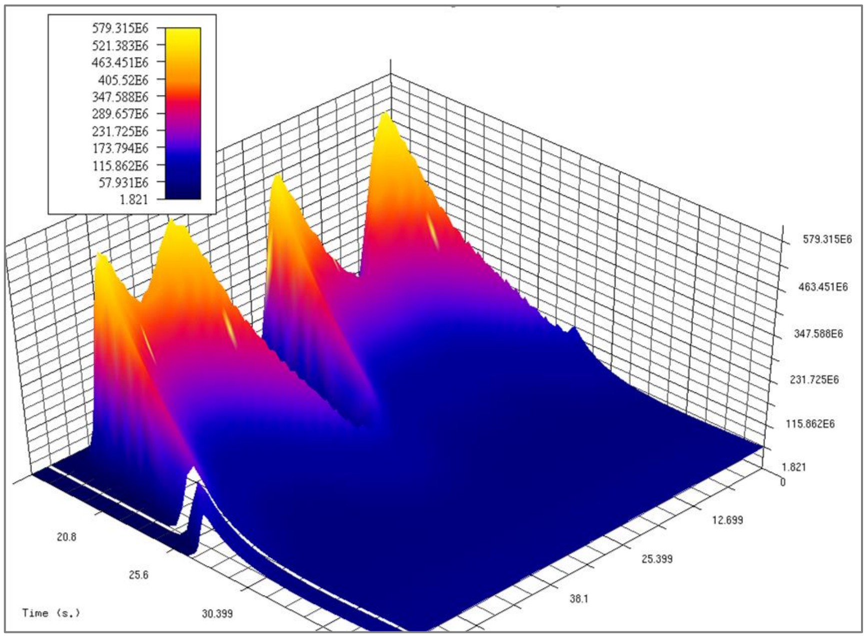
Solid and Litz Induction Coils; Transient Zone



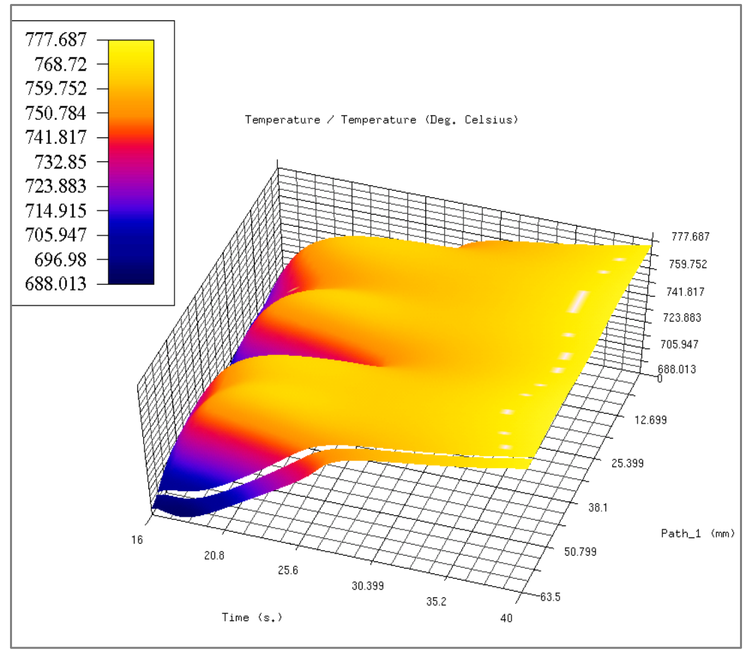


Solid inductor Litz inductor TZ – Transient Zones

Power Density and Surface Temperature



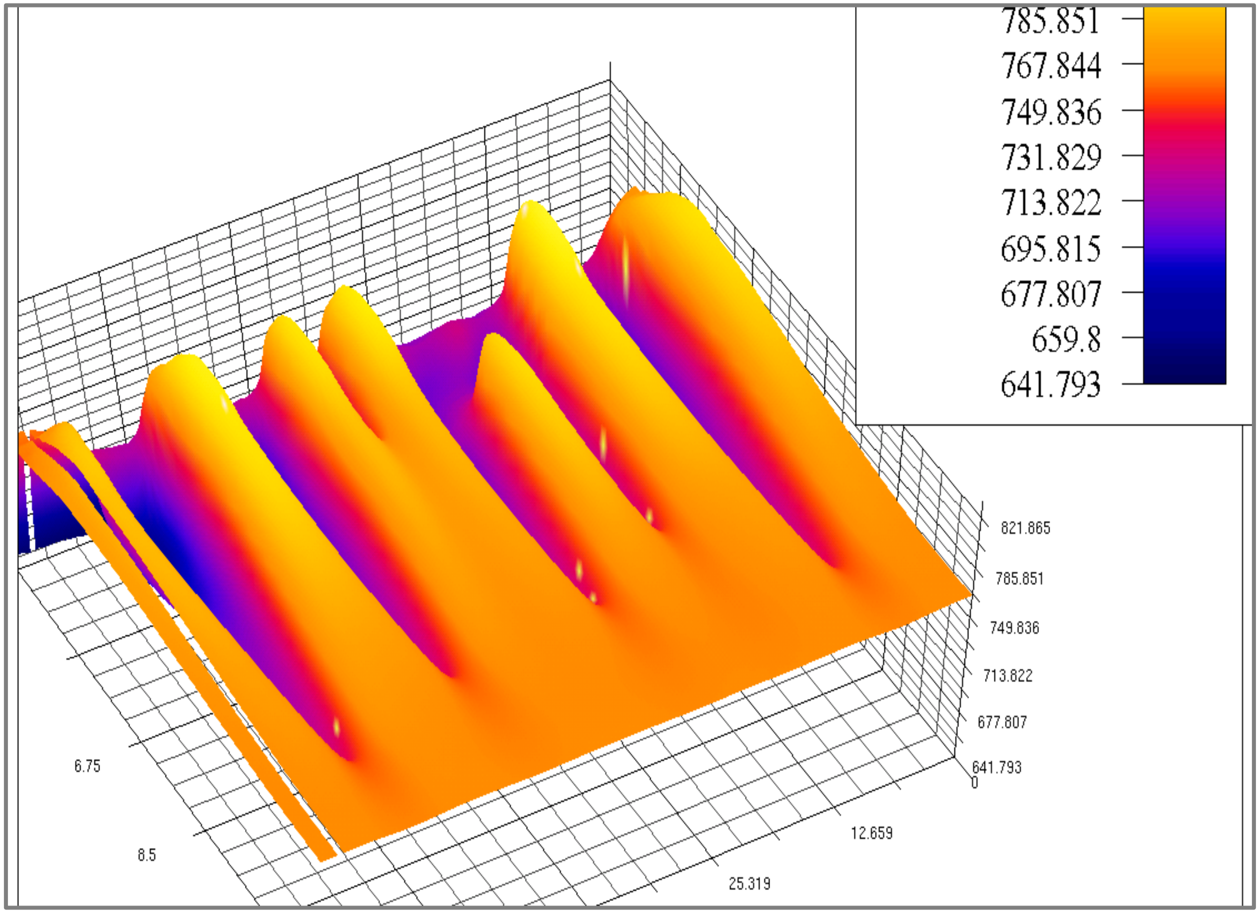
Power density variation at a depth of 0.1 mm under the surface. Ct = 16



Color map of temperature on the part surface. Ct = 16, time range 16-40 sec

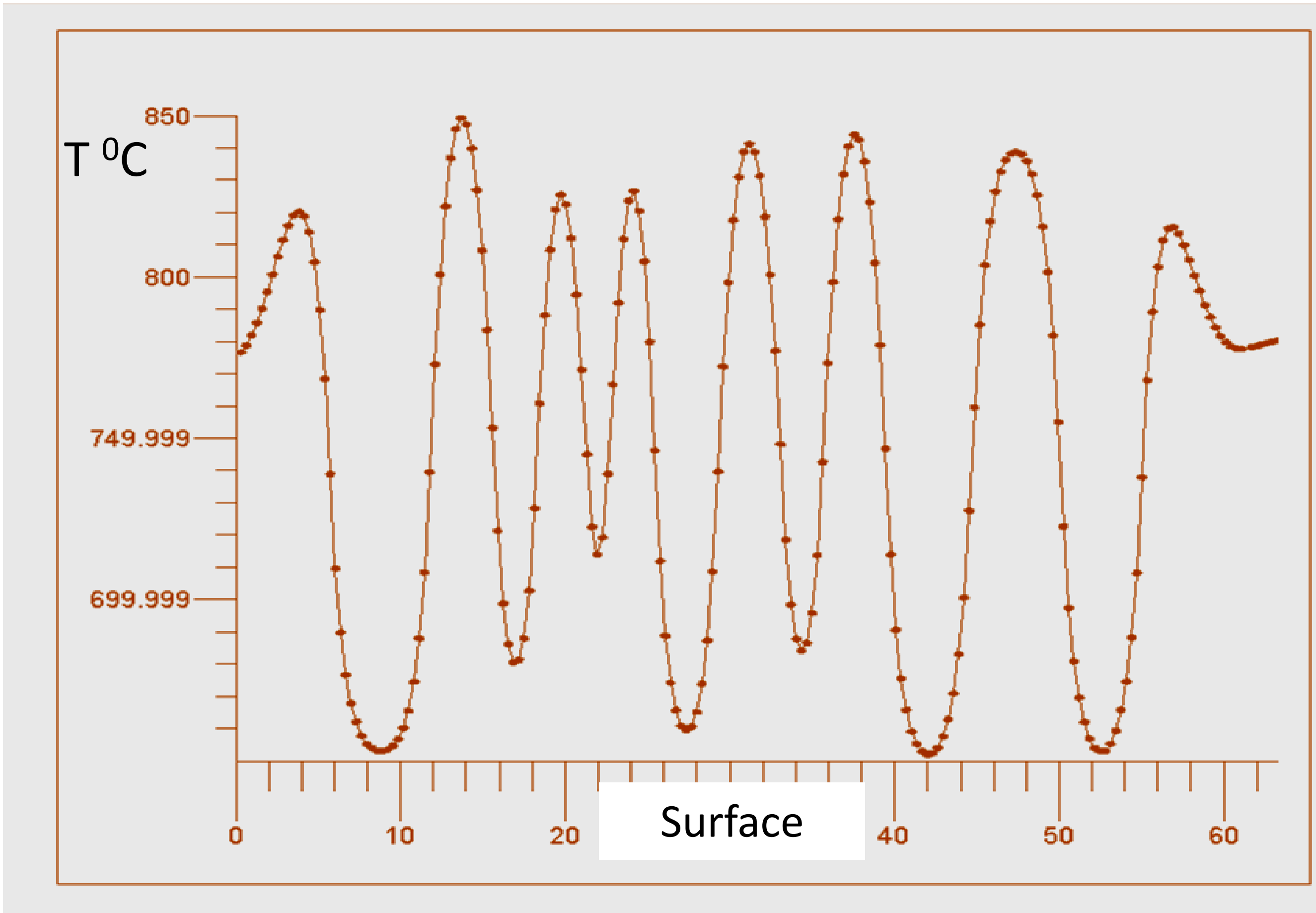
Frequency 20 kHz, I = 3000 A

More Temperature Distributions



F = 100 kHz, CT – 16, I = 2000 A

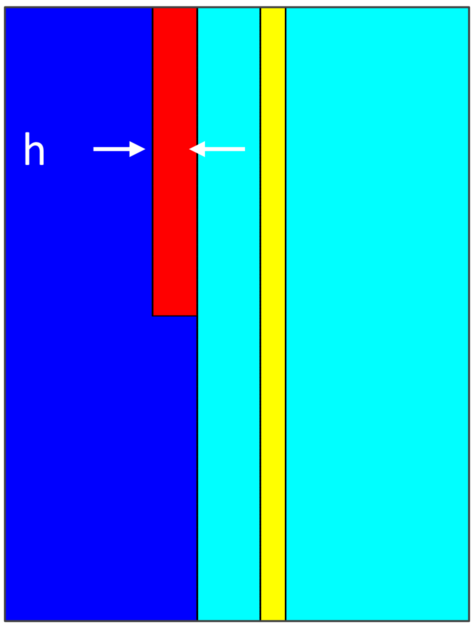
Temperature Profile at High Power

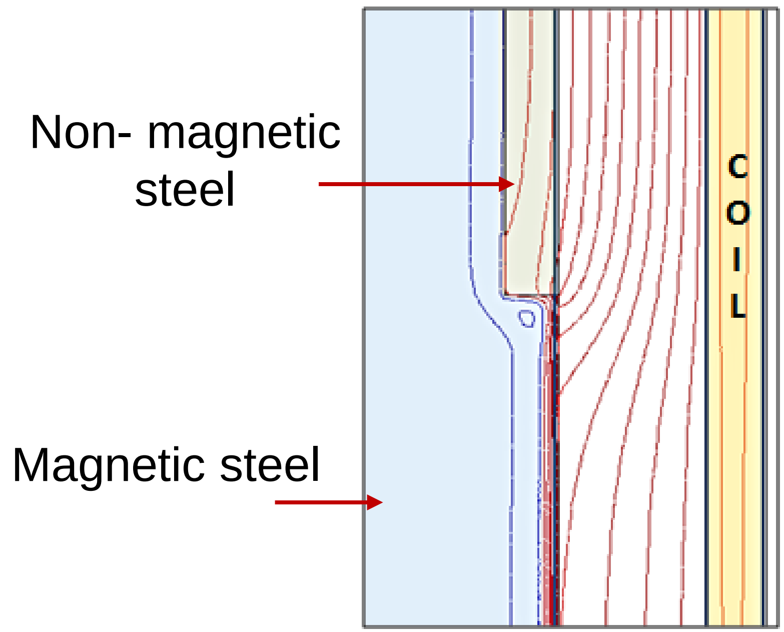


F = 100 kHz, CT – 16, I = 3000 A, t = 2 sec

New Explanation

Electromagnetic processes in the contact area of magnetic and two-layer bodies can explain zebra effect. It can be called “contact end effect”

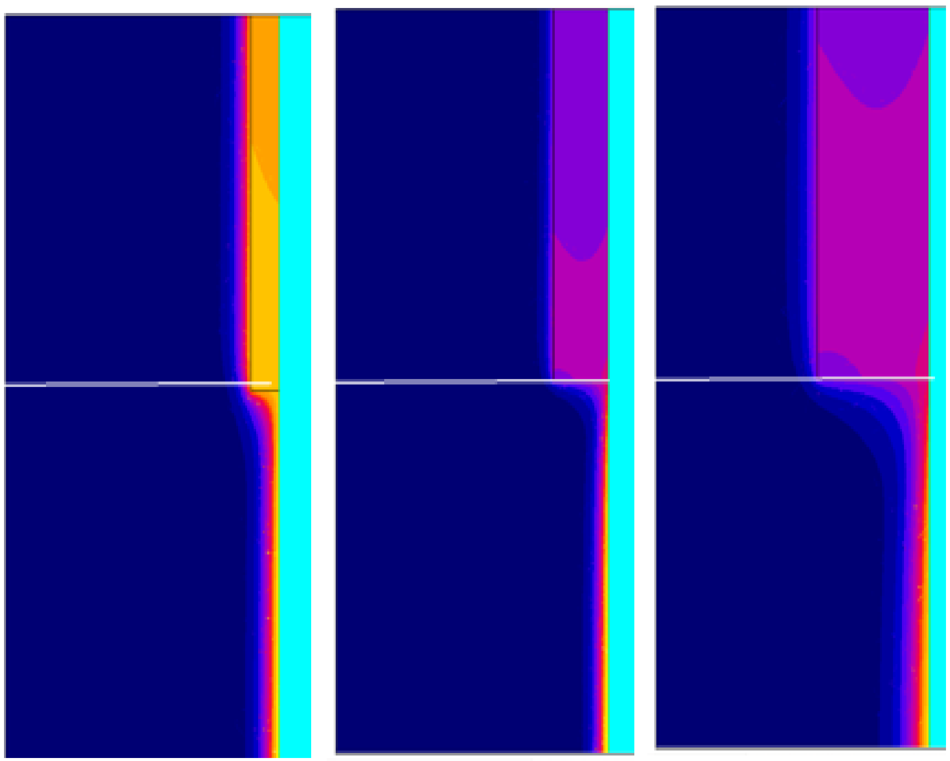




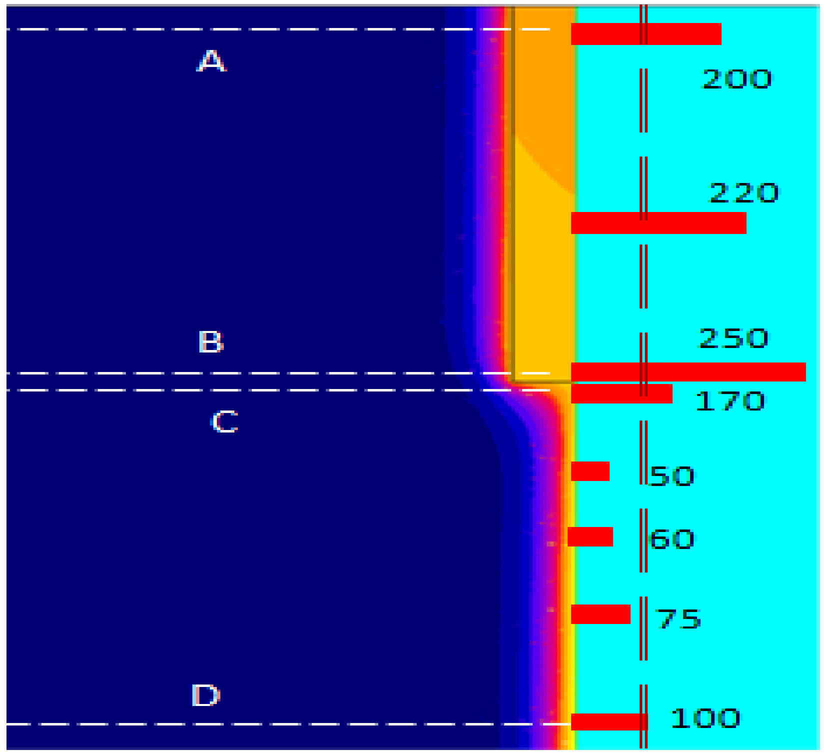
Coil – copper sheet; h = 0.2; 0.5δ and 1δ;
δ –reference depth for hot steel
Constant permeability of magnetic steel

Power Distribution in Contact Area

Study of electromagnetic processes in the area of contact "magnetic- two-layer" bodies. It can be called "contact end effect"

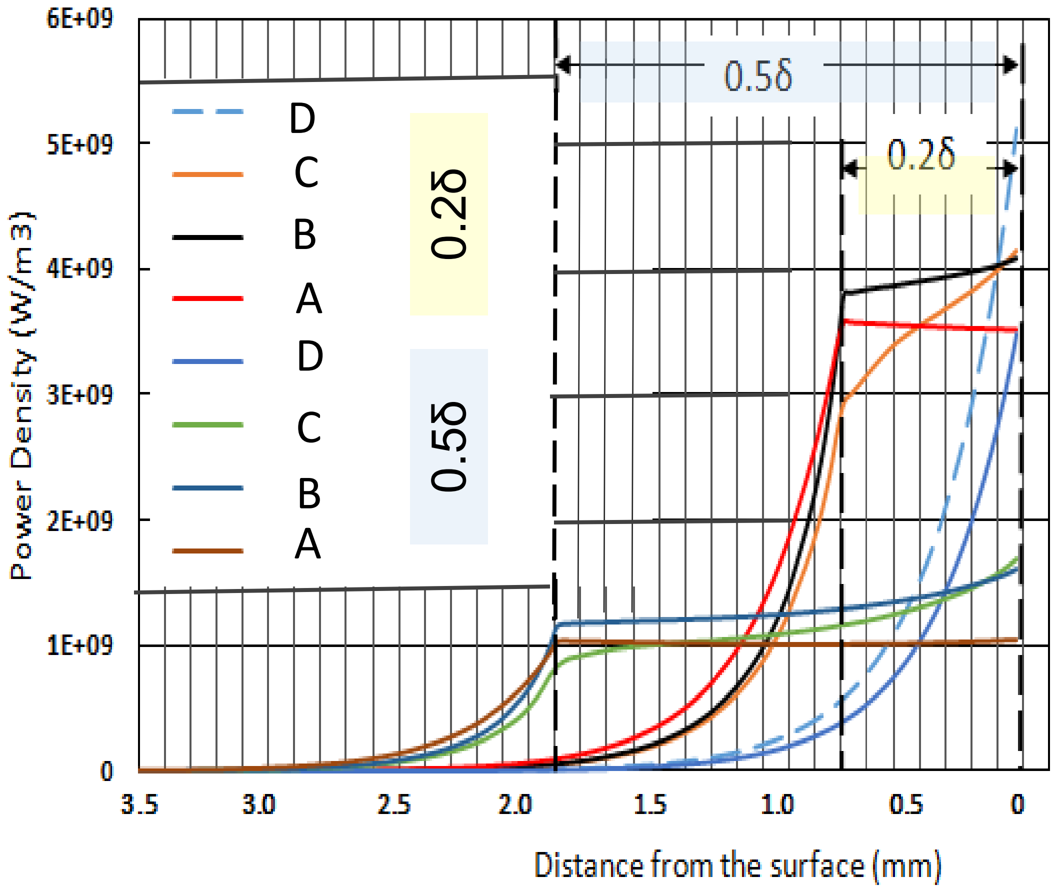


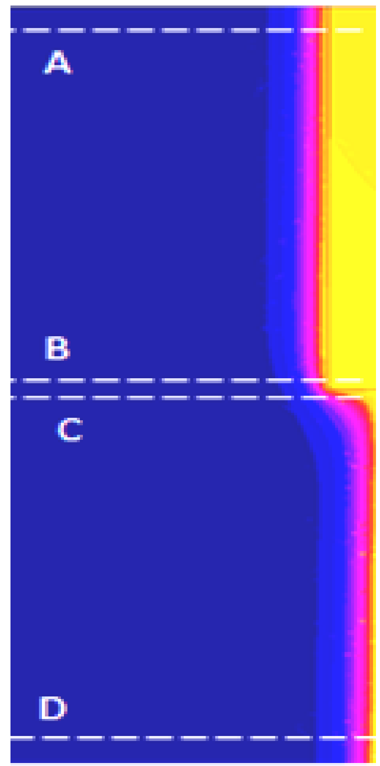
Color maps of power density for different thicknesses of non-magnetic layers: 0.2δ, 0.5δ and 1δ



Color map of power density and bars of linear power density. Non-magnetic layer is 0.2δ thick

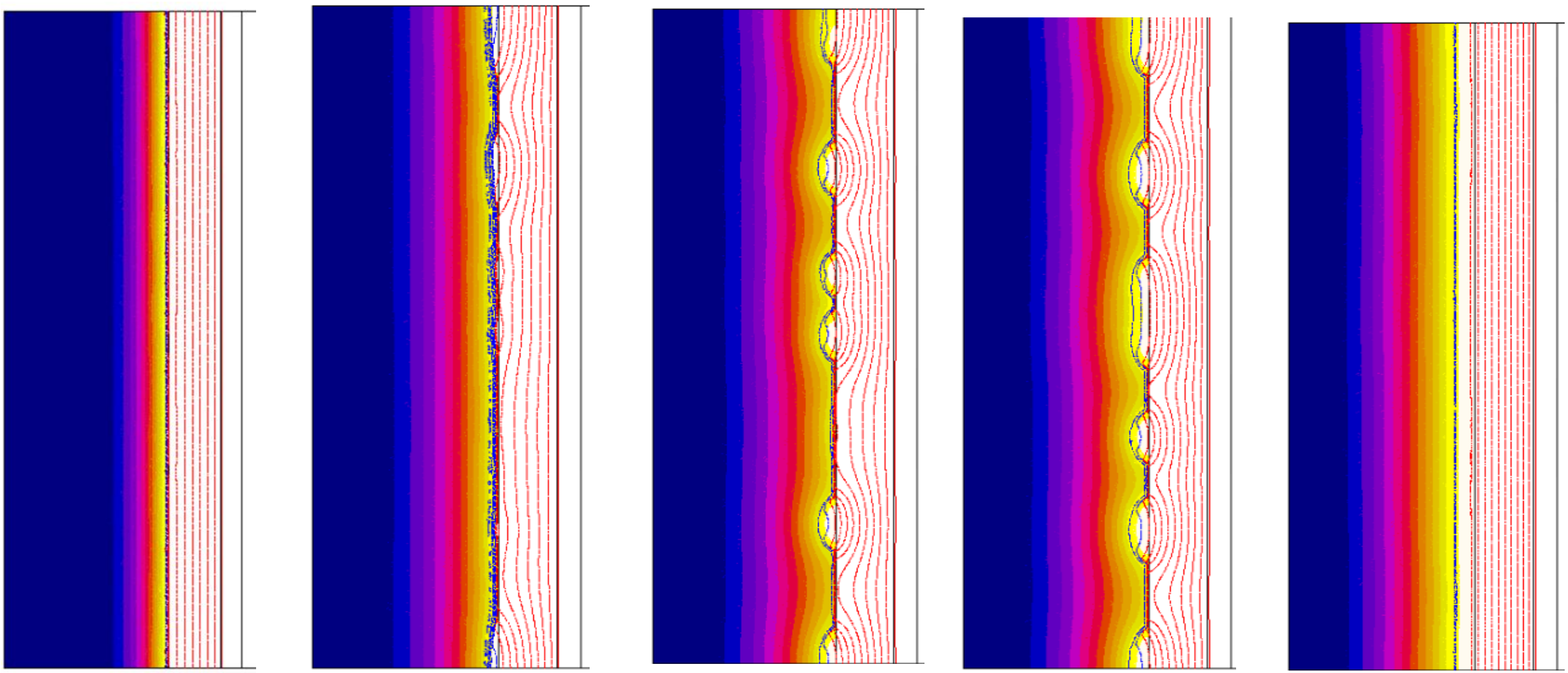
Power Distribution in Radius





Power density distribution in depth for non-magnetic layers of 0.2δ and 0.5δ. Dashed and solid blue lines are for a section D

Video



1 sec   4 sec   5.5 sec   6.5 sec   12 sec

F = 100 kHz, I = 2000 A

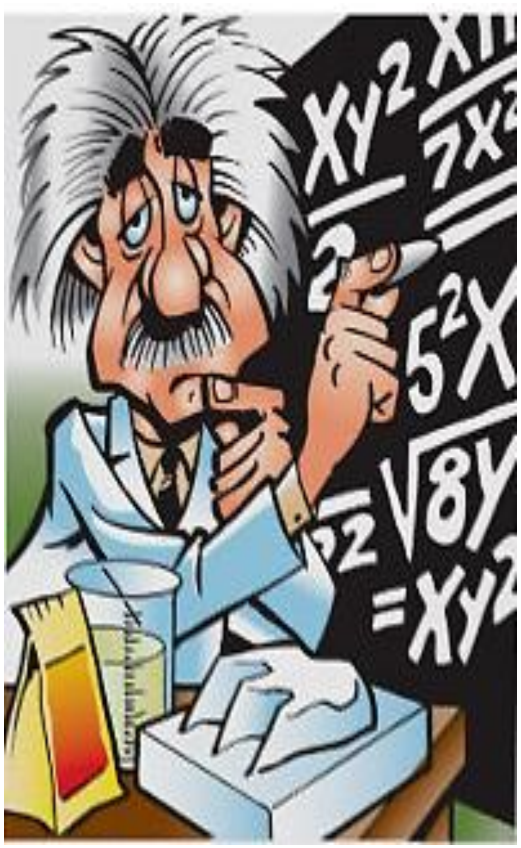
Conclusions

- Zebra effect is not well known and understood phenomenon
- Computer simulation using Flux 2D provides results that correspond well to previously published data (at least qualitatively…)
- "Contact end effects" explain observed phenomena very well
- It is difficult to expect that performed simulation corresponds accurately to experiments for two major reasons:

  - Accuracy of harmonic approach isn't proved for such extreme conditions

  - Profound study of magnetic properties near Curie point for a given steel must be made in experimental tests
- It isn't clear how much zebra phenomenon can influence practice of induction heating and how it can be used beneficently
- We can expect more effects of instability in induction heating including spotty pattern …..

Post Scriptum



It looks like we explained zebra effect but more study required…..