COMSOL CONFERENCE 2015 GRENOBLE

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Iterative procedure to account for nonlinear magnetic properties of steel in inductive heating simulations

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A world leader in premium tubular solutions

2014
Key figures

Sales volume
2,323kt

Sales
€5,701m

EBITDA
€855m

- **Serving the Oil & Gas, Power Generation and Industry activities**
- **Worldwide presence with 23,000 employees* in more than 20 countries**
- **Over 50 production facilities worldwide delivering a large spectrum of products for diversified applications**
- **Highly innovative with 6 advanced R&D and connection test centers located in France, Germany, Brazil and the U.S.**
- **A clear and constant strategy:**
  - **more premium, more local, more competitive**

** At December 31, 2014 (permanent and temporary contracts)*

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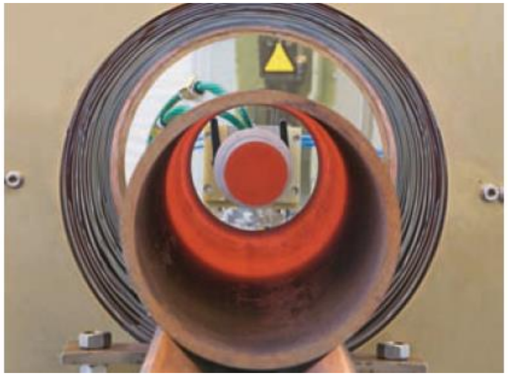
Induction heating in the VALLOUREC Group

- **In VALLOUREC, induction heating process is used for:**
  - **Pre-heating of pipe ends**
  - **Hardening and tempering of products (austenization,…)**
  - **Stress relieving of oil & gas pipe**
  - **Drying of pipe coatings**

Pipe end preheating

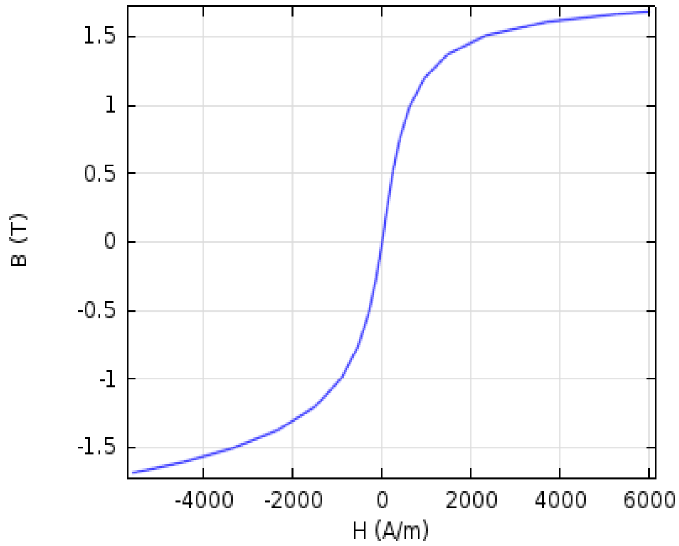
Hardening and Tempering



Stress relief

Framework

- **To be able to accurately optimize induction heating processes, it is important to correctly include nonlinearities**
  - relationship between the magnetic flux and the magnetic field intensities



Example of magnetic flux vs. magnetic field relationship

- **Finding the exact solution to this problem implies the use of time-dependent solvers which lead to extremely high computation times**

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ITERATIVE METHOD

- **To overcome this difficulty, a method extracted from literature was implemented in COMSOL Multiphysics**
  - *Calculation of Eddy Current Losses in Nonlinear Ferromagnetic Materials*
    Dimitris LABRIDIS and PETORS DOKOPOULOS
    IEEE TRANSACTION ON MAGNETICS. Vol 25 NO. 3. MAY 1989

- **This method is iterative and solves at each loop a frequency problem with a fictive linear magnetic material**
  - It introduces a fictive equivalent relative magnetic permeability μ_r^f
  - μ_r^f is evaluated at each step and for each node based on a magnetic co-energy conservation equation
  - The aim is to obtain the same eddy current losses for the fictive linear material and for the real nonlinear material

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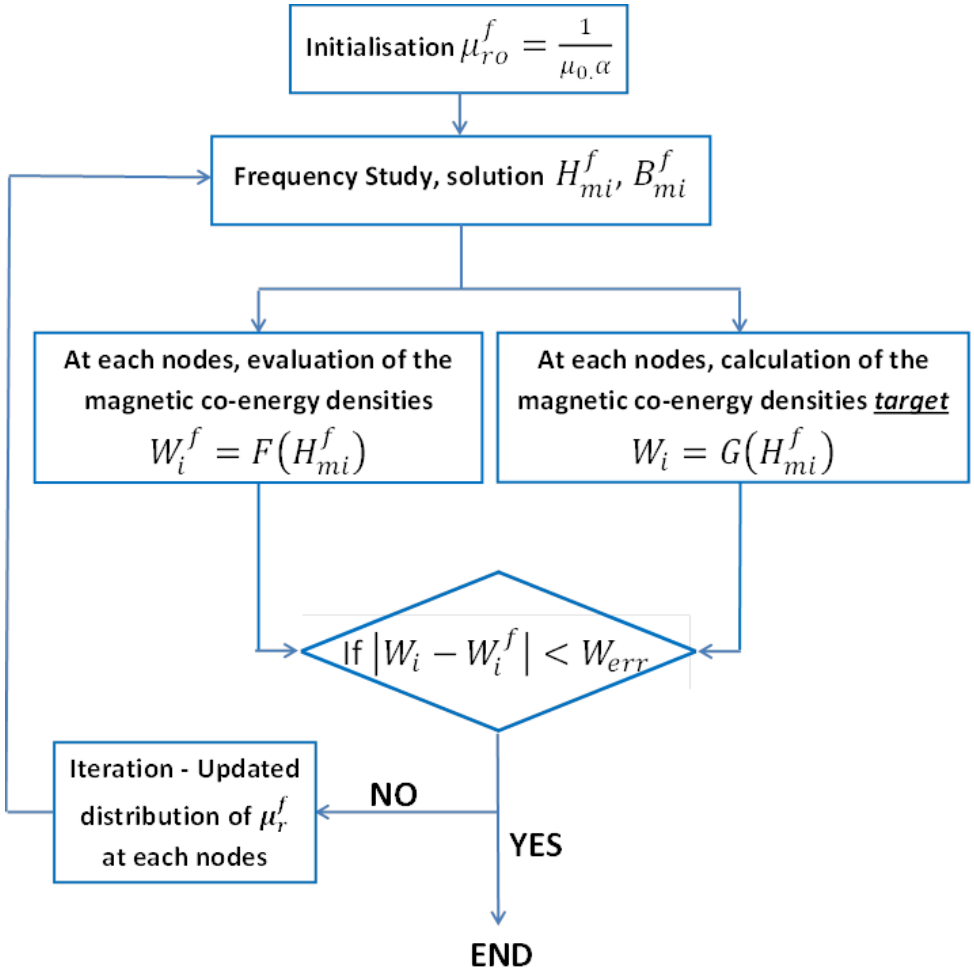
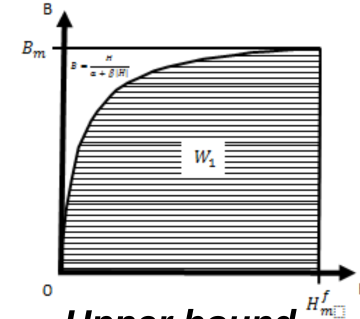
COMSOL IMPLEMENTATION

- **The procedure implemented in COMSOL uses segregated solvers.**

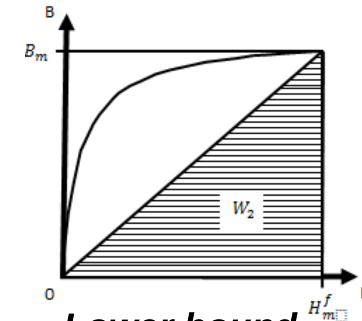


TARGET CO-ENERGY ESTIMATION

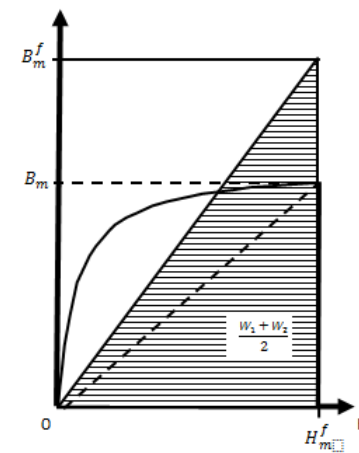
- **The target co-energy is based on estimations of upper and lower bounds for the eddy current losses.**
  - The upper bound (W1) is related to the integration of the H-B curve. This takes into account the saturation of the material.
  - The lower bound (W2) is related to the average value of the slope dB/dH
- **The target co-energy is the average of W1 and W2**
  - According to the methodology, this value should ensure that the fictive material has eddy current losses similar to those of the real material



Upper bound



Lower bound



Co-energy average

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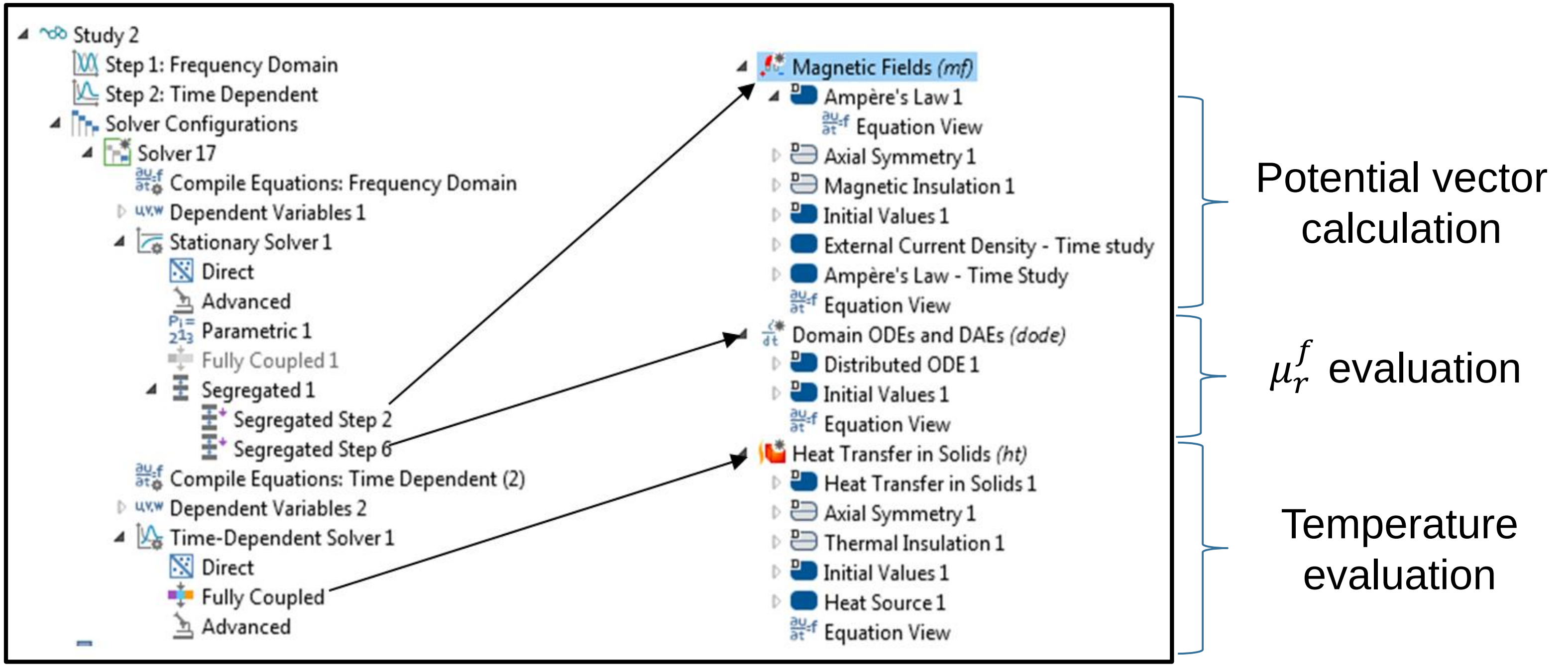
COMSOL IMPLEMENTATION

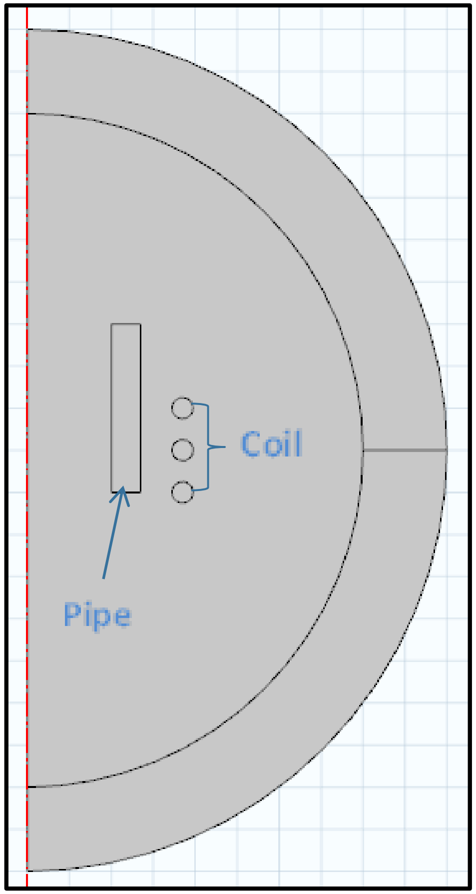
- **The resolution is shared in two steps.**
  - **The first one is a frequency resolution dedicated to solve the potential vector A and fictive magnetic permeability μ_r^f**
  - **The second one is a time depend resolution devoted to solve thermal pattern**



COMSOL implementation

EXAMPLE OF APPLICATION

- **The geometry is composed of a three turns coil and a pipe surrounded by air.**
- **The model is 2D axisymmetric.**
- **The coil is made of copper whereas the pipe is made of steel.**
- **The studied frequency is 50 Hz.**
- **The initial pipe temperature is 20°C.**
- **Convective and radiative exchanges are *not* taken into account in this simulation**



GEOMETRY overview

Simulations and comparison description

- **Two simulations have been carried out:**
  - *Time dependent study simulation*
  - *Frequency iterative simulation*

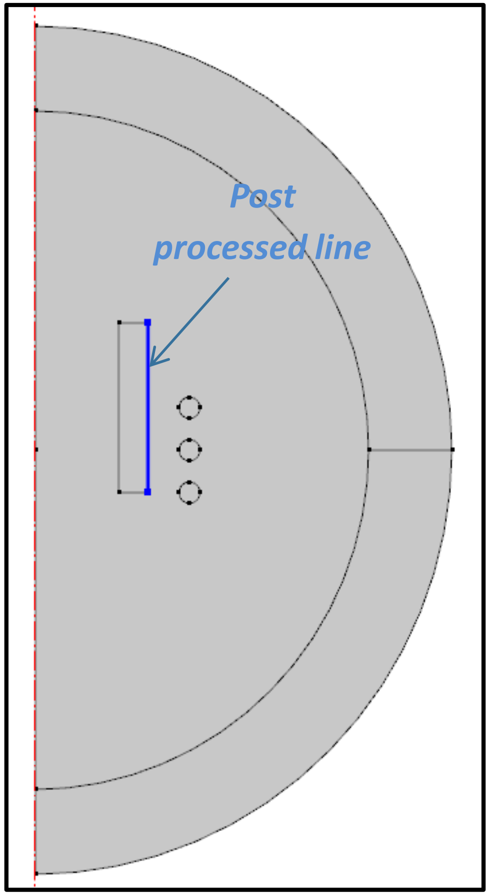
- **For the *time study simulation* the thermal and Maxwell's equations are solved by the time dependent solver which provides the reference solution to the problem.**

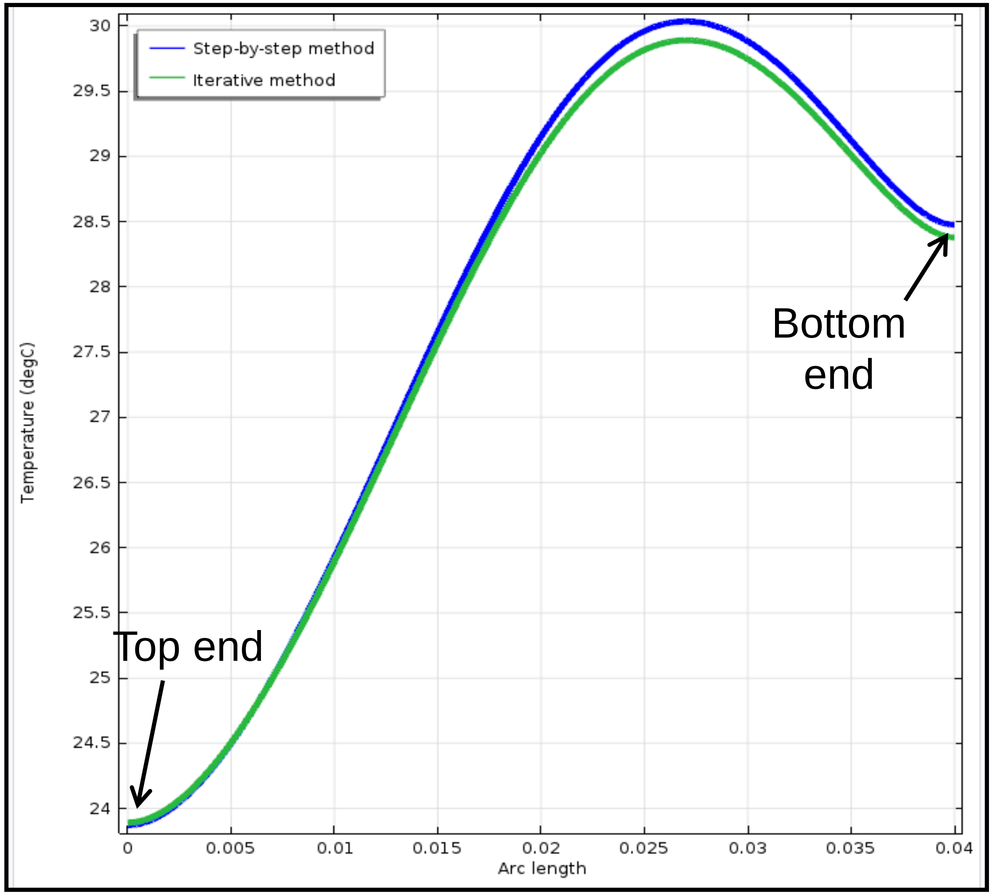
- **The results obtained by the iterative method have been compared to the classical step by step solution.**

- **The comparison has been done in terms of temperature pattern and computational times.**

RESULTS COMPARISON

- **Temperature after 5 seconds of inductive heating**





<u>Temperatures along the pipe Outer diameter</u>

RESULTS COMPARISON

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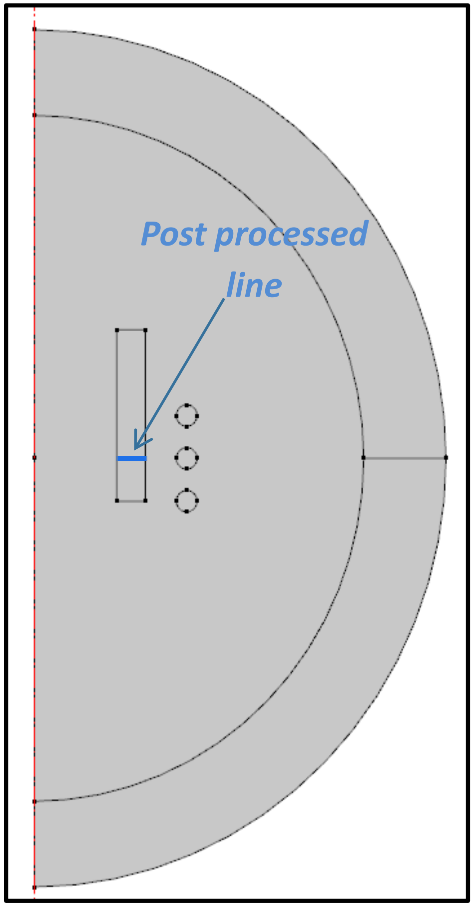
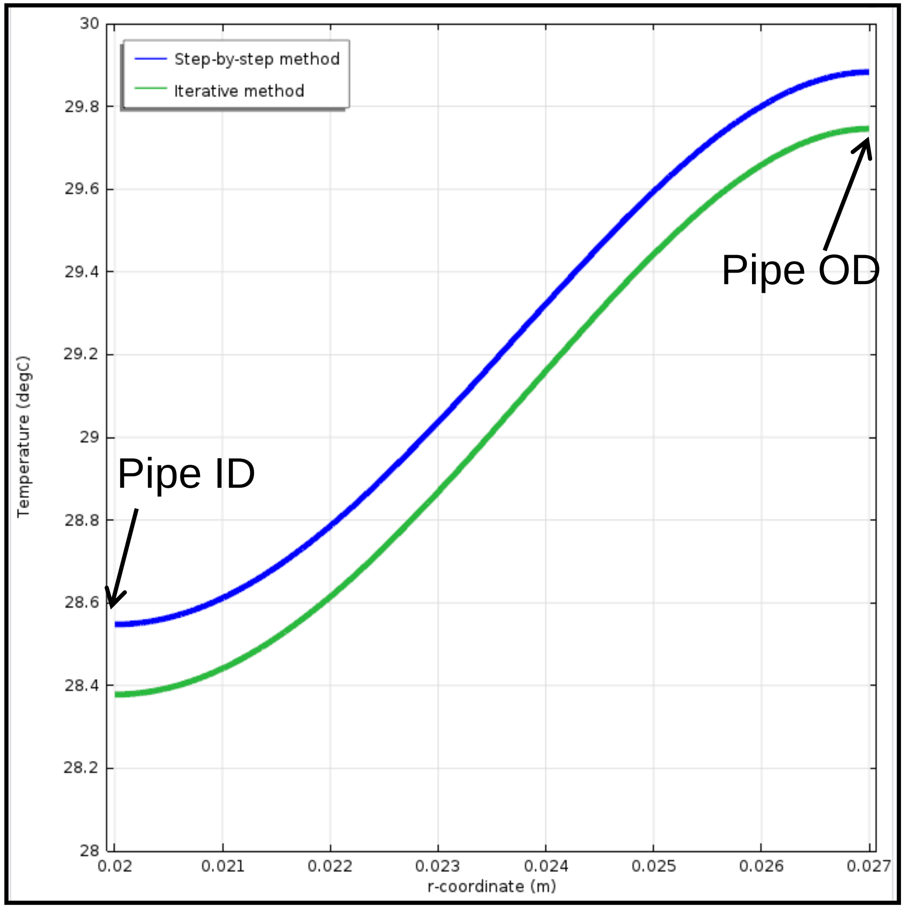




<u>Temperature through the pipe wall</u>

CONCLUSION

- **The method implementation feasibility has been proven for a simple geometry.**

- **The agreement between the two methods is very good.**
  - After 5 seconds the maximal temperature difference is 0.2°C at the middle of the coil the mean temperature of the pipe wall is 29°C instead of 29.2°C for the classical step by step solution that means a difference of 2%.

- **For this simulation, the iterative method is 140 times faster than the classical step by step method.**

Methods	Duration
Step by step	1hrs 30 min
Iterative	39s

Computation times for 5s of simulation

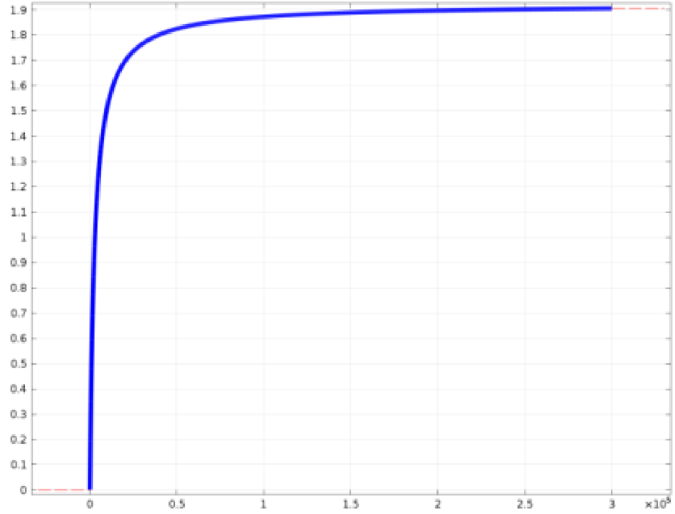
THANK YOU

ANY QUESTIONS ?

Frolich approximation

- **Frolich approximation has been used for modeling the non linear B-H relation:**

B



B

H

$$B = \frac{H}{\alpha + \beta |H|}$$