Magneto-Mechanical-Thermal Couplings with Linear Assumptions for the Pulsed Magnetic Compression of Tubes with Single-Turn Coils

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Introduction

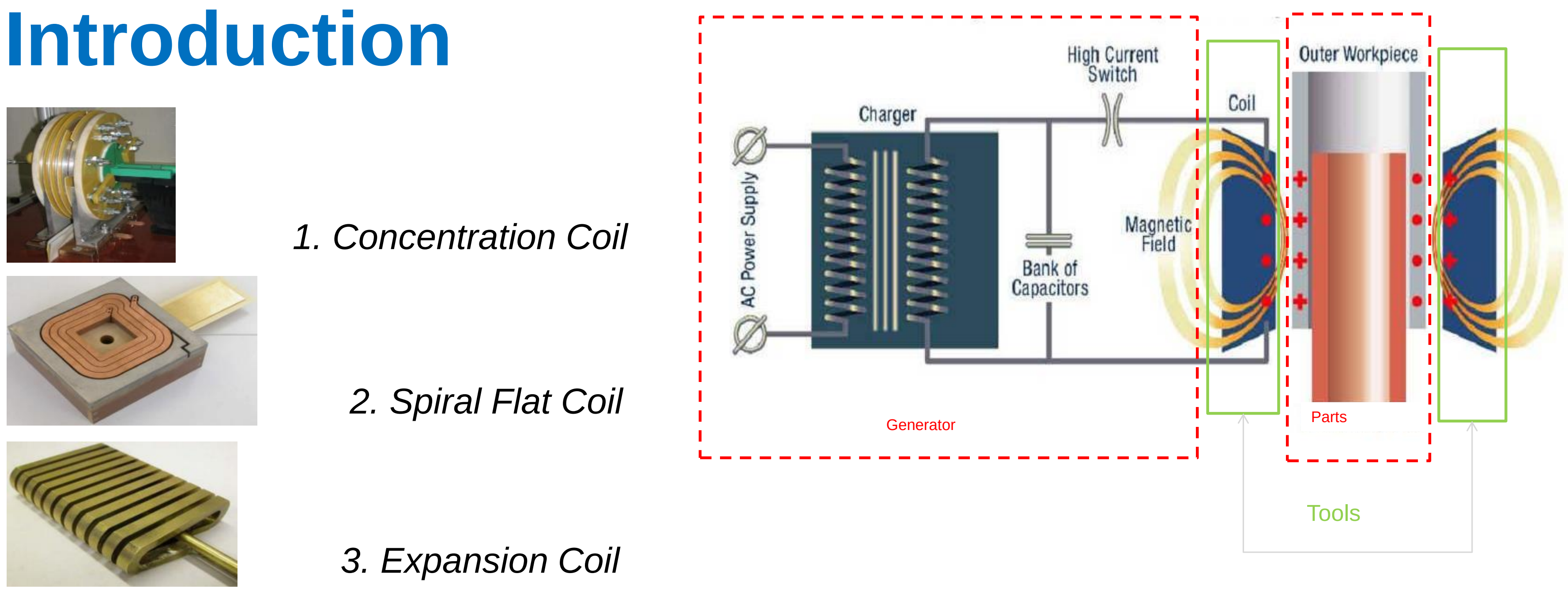


***Figure 1**. Coils for pulsed electromagnetic forming technologies.*

The 2D axi-symmetrical numerical model (see [1] and Figure 2) provides us a reference to test the accuracy and reliability of an equivalent analytical solution [2].

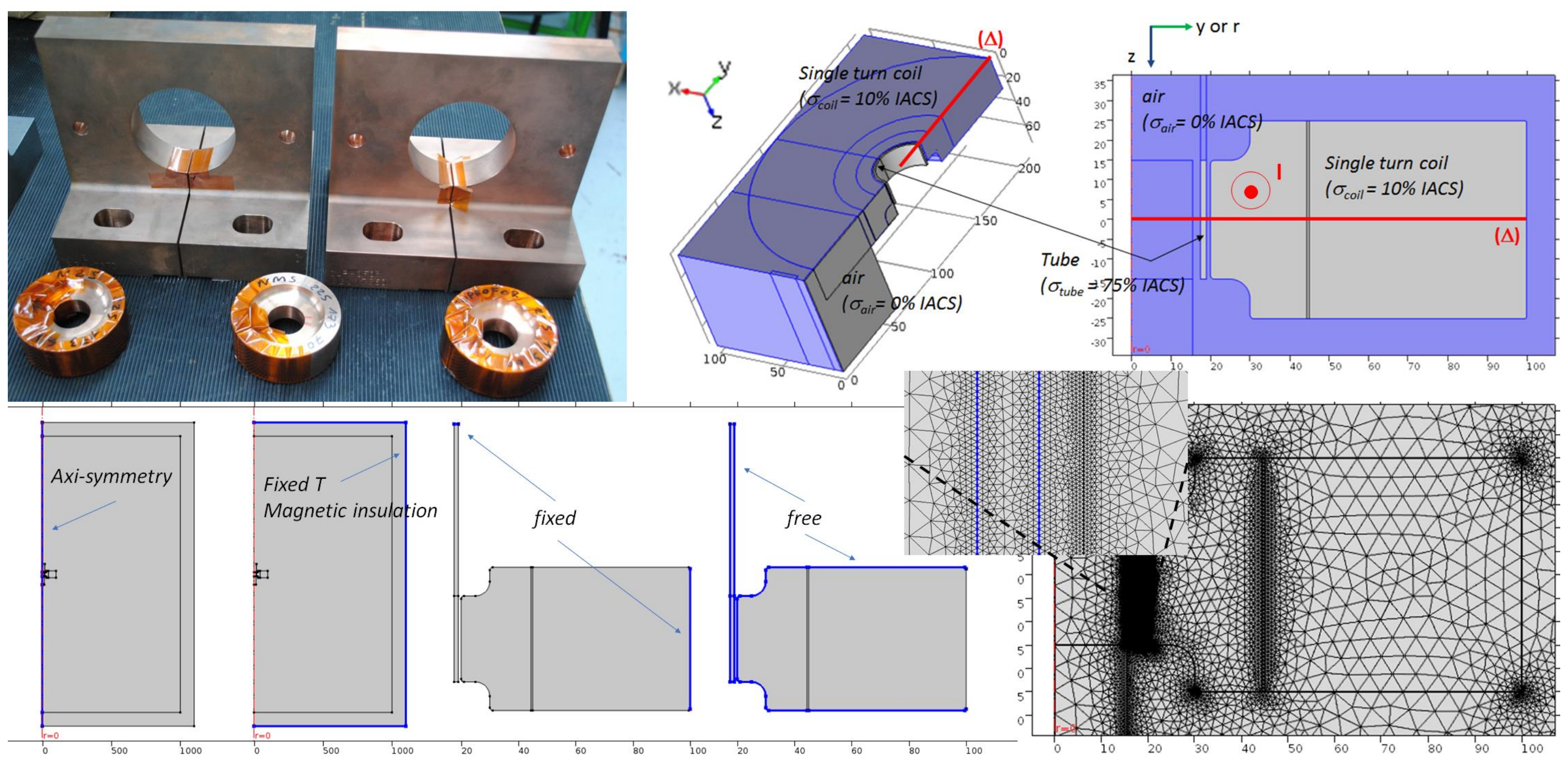
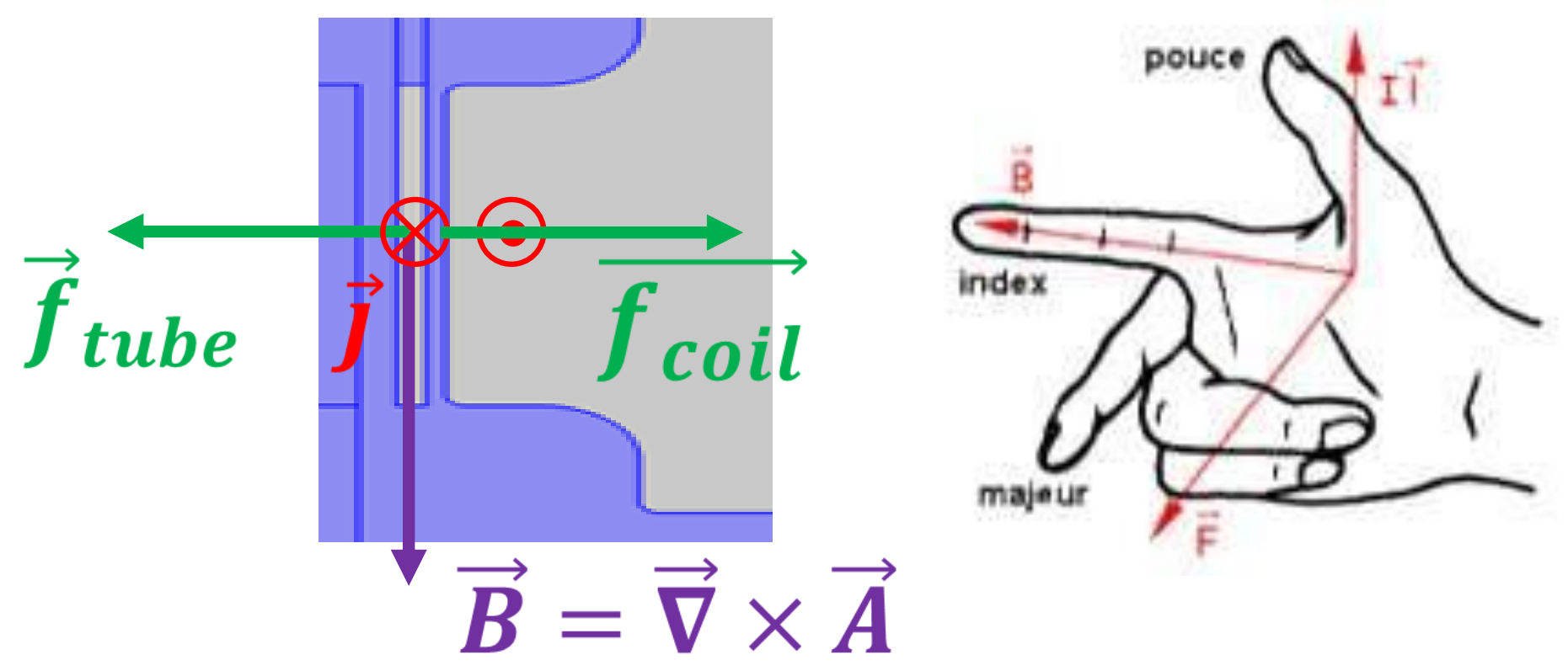


***Figure 2**. Geometry of the single-turn coil for tubes compression.*

Eddy currents interact with the field (see Figure 3)
⇒ Lorentz force ⇒ magneto-mechanical coupling
⇒ heat losses ⇒ magneto-thermal coupling

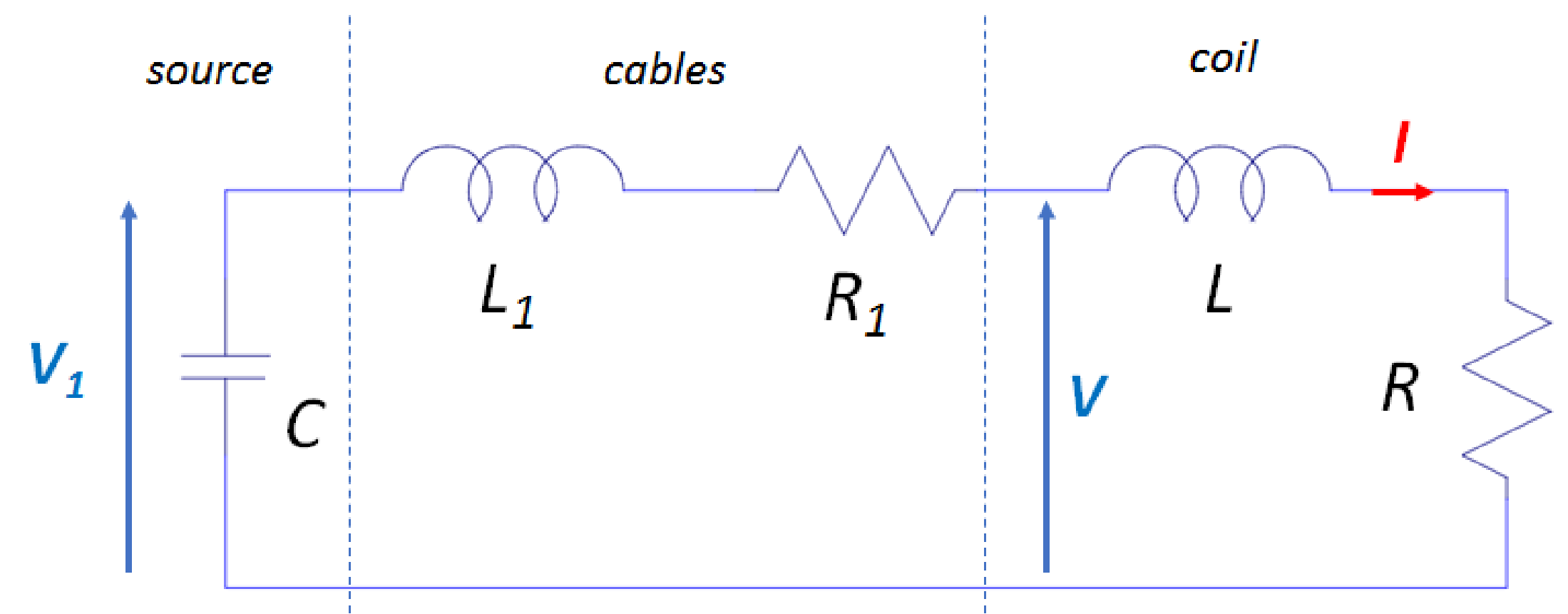
***Figure 3**.*
Eddy currents and Lorentz force principles.



Governing equations and weak coupling

Electrical circuit

***Figure 4**.*
Equivalent circuit



$C = 138\ \mu\mathrm{F}$, $L_1 = 210\ \mathrm{nH}$, $R_1 = 11.5\ \mathrm{m}\Omega$

Magnetic field

$$\vec{\nabla} \times \mu^{-1} \vec{\nabla} \times \vec{A} = \vec{j} = -\sigma(T)\left(\partial_t \vec{A} + \vec{\nabla} V\right)$$

A is the magnetic vector potential, σ is the electrical conductivity (σ_{coil} = 10% IACS, σ_{tube} = 75% IACS, σ_{air} = 0 taken as constants here), μ is the magnetic permeability ($\mu = \mu_0 = 4\pi.10^{-7}\ \mathrm{H^{-1}m^{-1}}$). The couplings with other physics here occur with the change in geometry due to strains and the temperature dependent electrical conductivity.

Structural mechanics

$$\vec{\nabla} \cdot \left(\overline{\overline{s(\epsilon, T)}}\right) = -\vec{f} = -\vec{j} \times \vec{\nabla} \times \vec{A}$$

ε is the elastic mechanical strain, s is the mechanical stress. No temperature dependence is taken into account in the following results but can be included. The behaviour considered here is the elastic one $s = E\varepsilon$, with E_{tube} = 120 GPa and E_{coil} = 210 GPa.

Thermal

$$C_p \partial_t T = \vec{\nabla} \cdot \left(-k \vec{\nabla}(T)\right) + \sigma^{-1} j(A)^2$$

T is the temperature, C_p is the heat capacity per unit volume, k is the thermal conductivity (*Steel alloy in coil and copper alloy in tube*)

Results

(Figures 5-8) show the instantaneous radial force, stress, strain and temperature profiles vs the radius *r* for a given generator & coil.
(Figures 9-12) show the transient surface & max. force, stress, strain and temperature vs time.

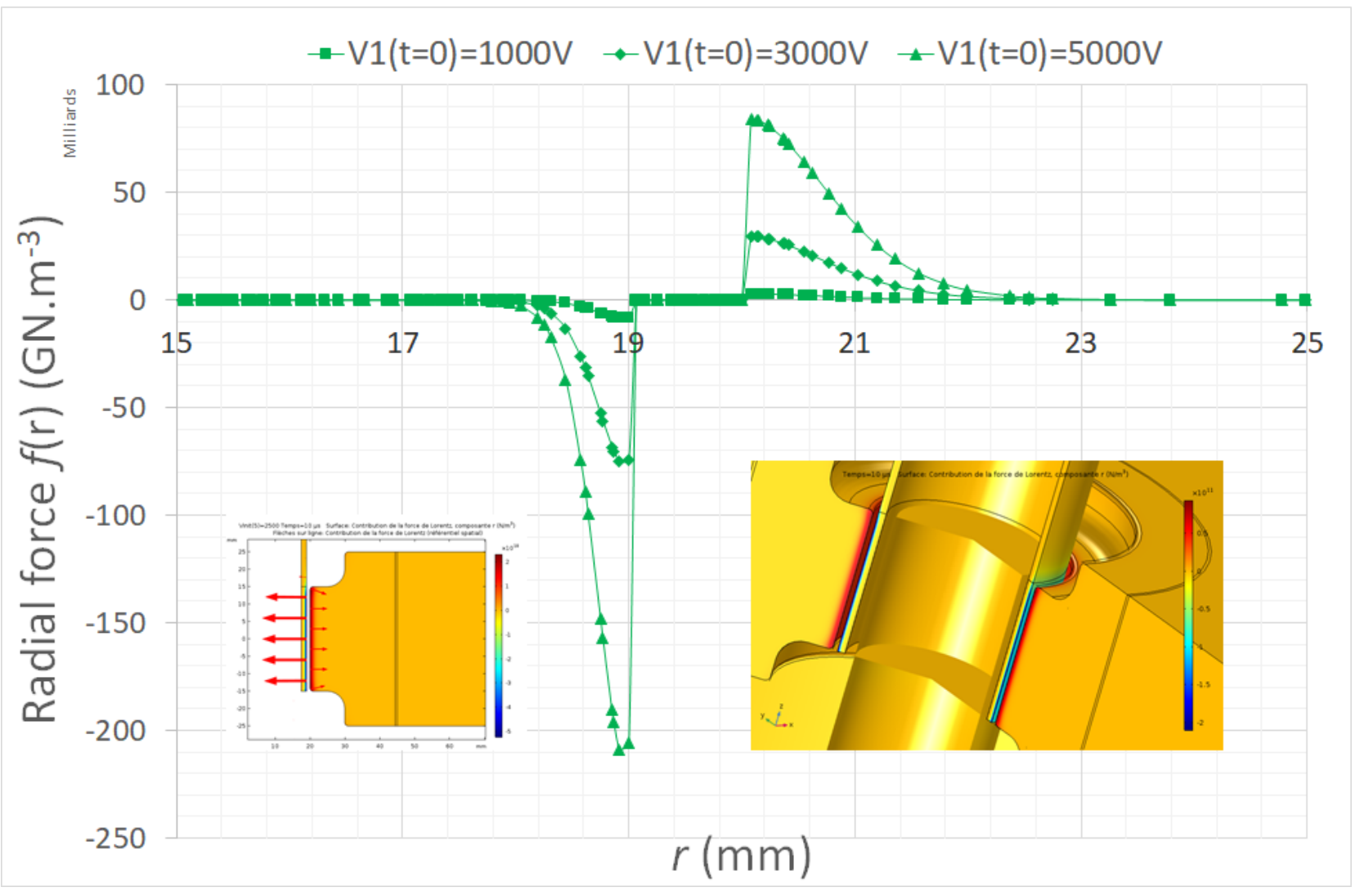


Figure 5. $f(r) \in (\Delta)$ @ t=10 us.

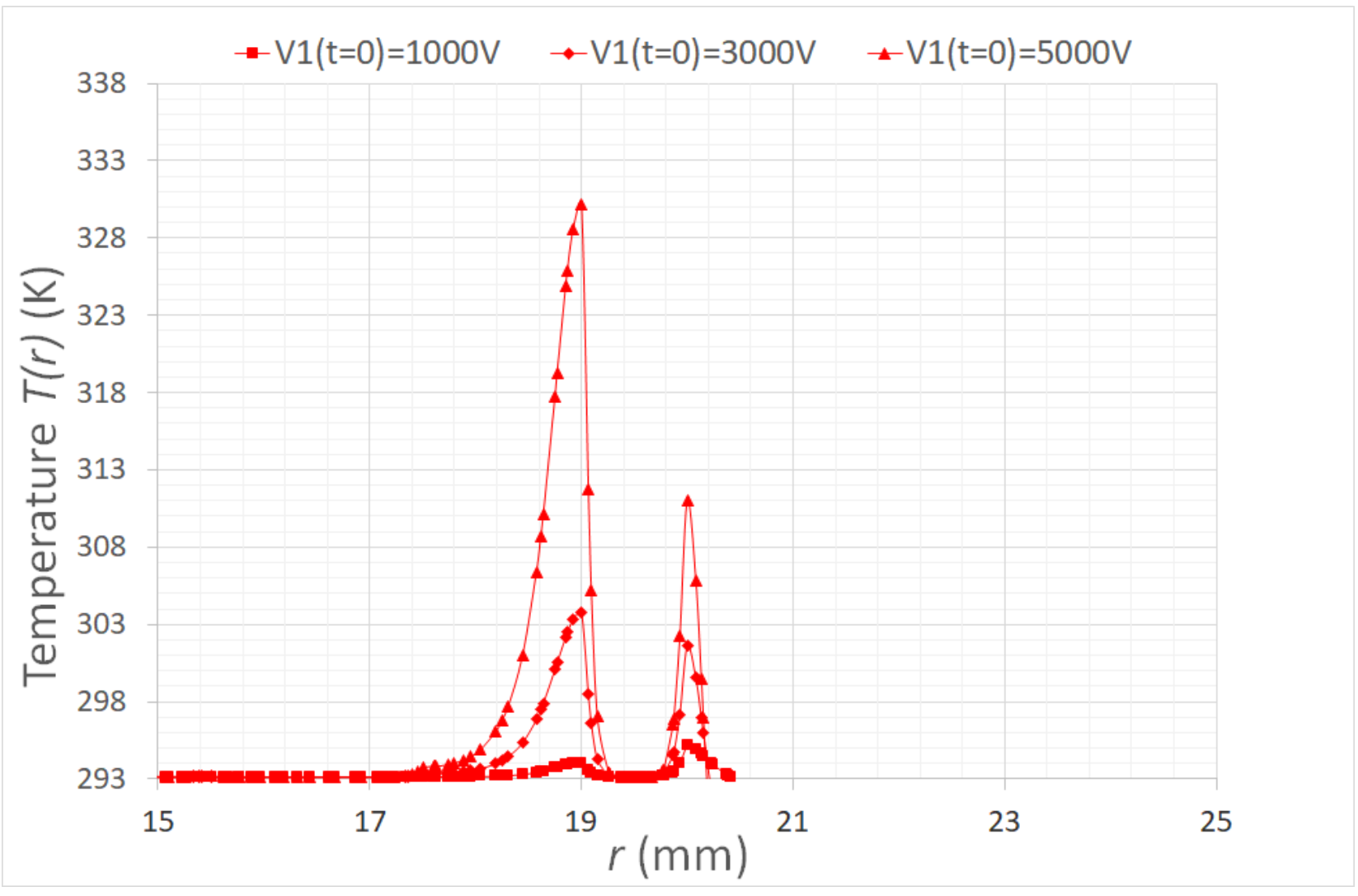


Figure 8. $T(r) \in (\Delta)$ @ t=200 us.

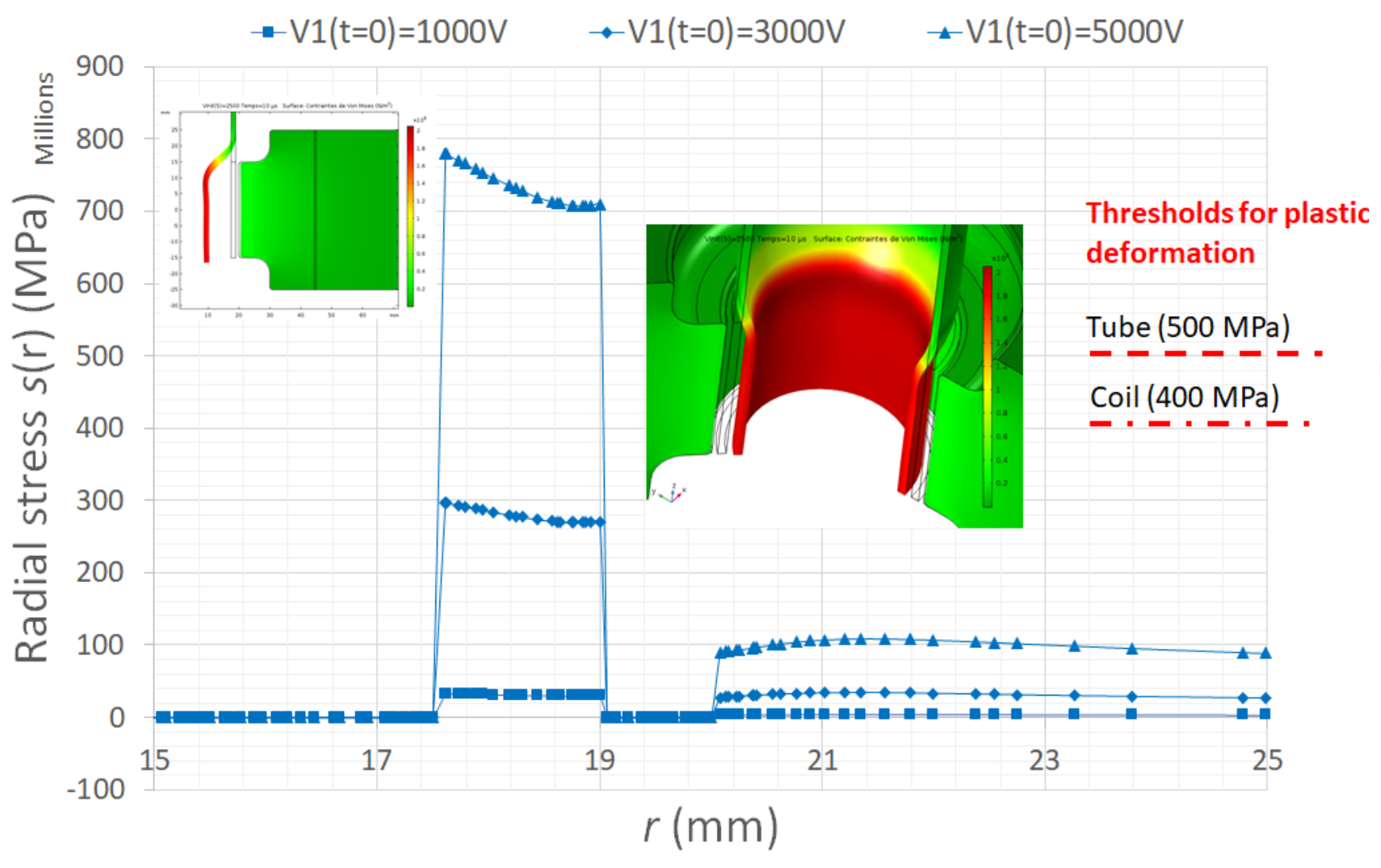


Figure 6. $s(r) \in (\Delta)$ @ t=10 us.

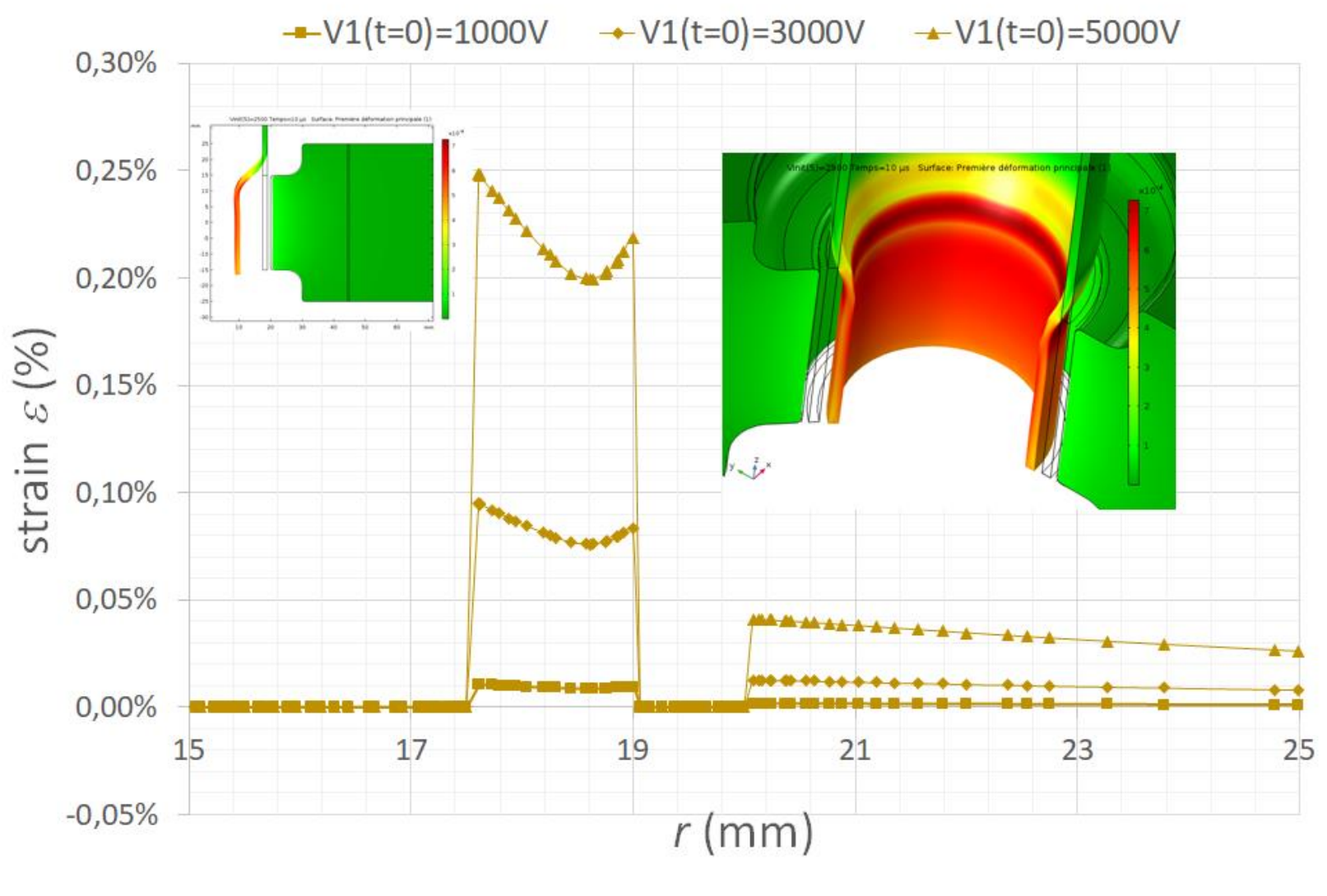


Figure 7. $\varepsilon(r) \in (\Delta)$ @ t=10 us.

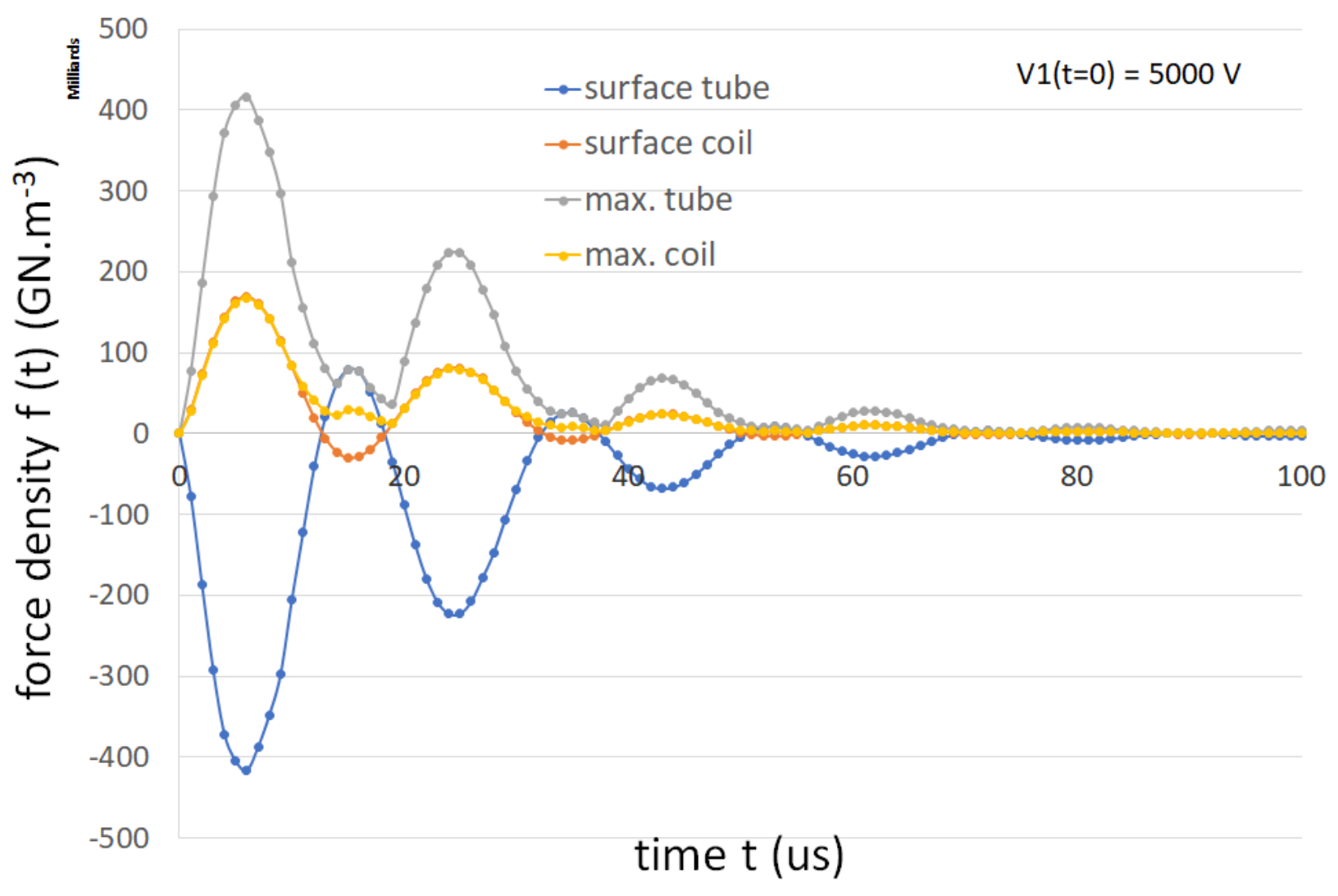


Figure 9. Coil & tube $f_{max}(t)$ & $f_{surf}(t)$.

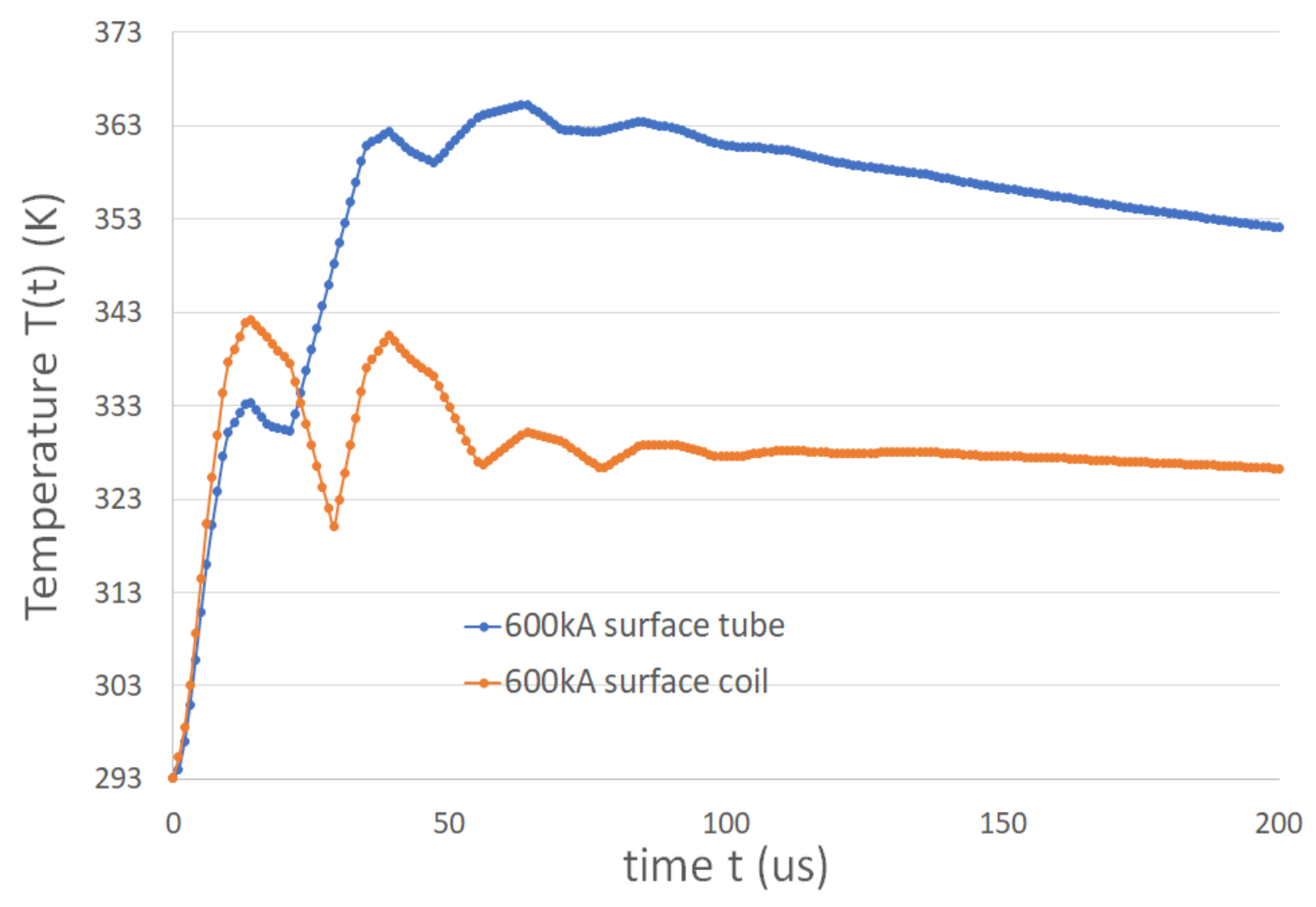


Figure 12. Coil & tube $T_{max}(t)$.

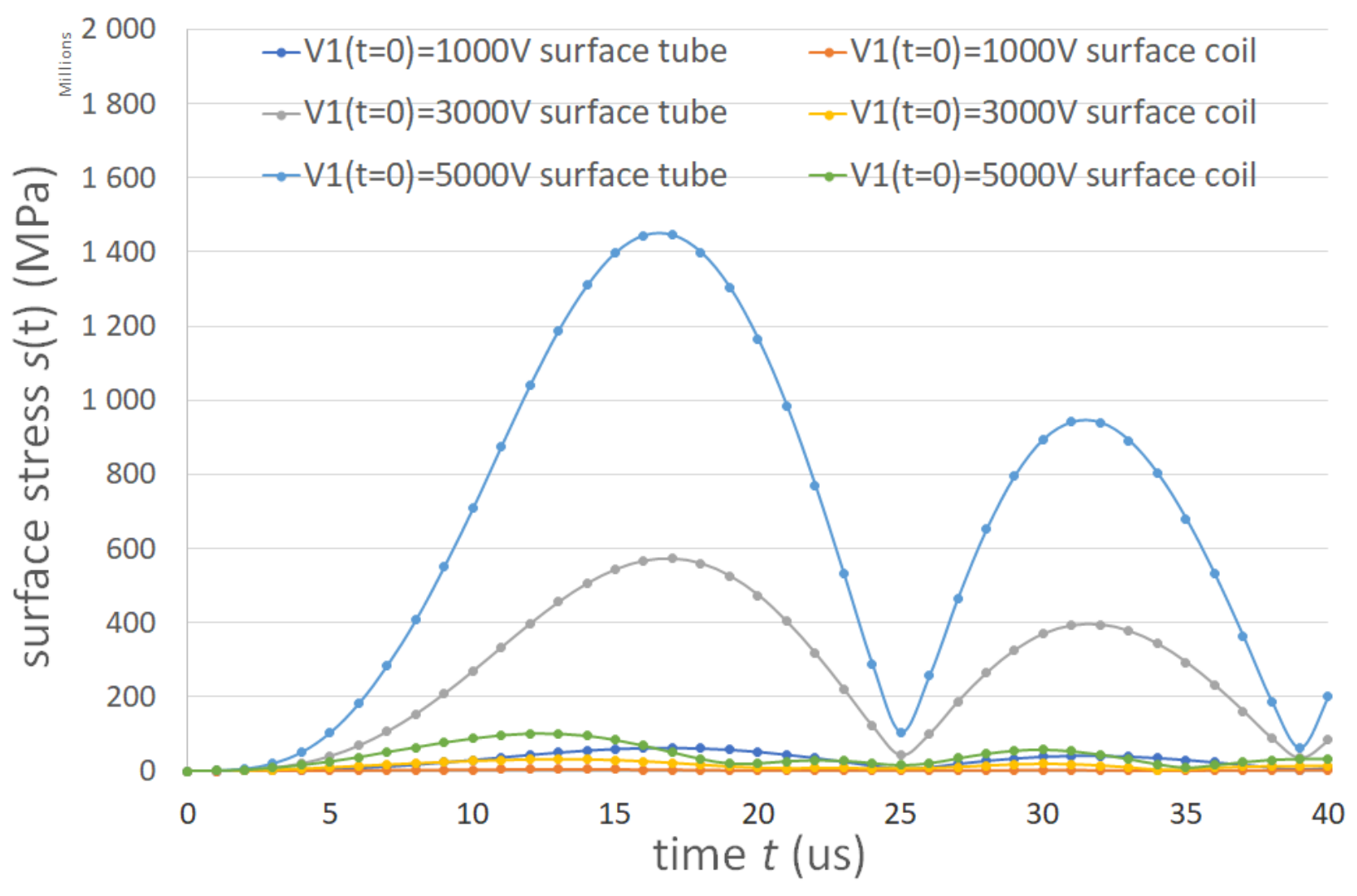


Figure 10. Coil & tube $s_{surf}(t)$.

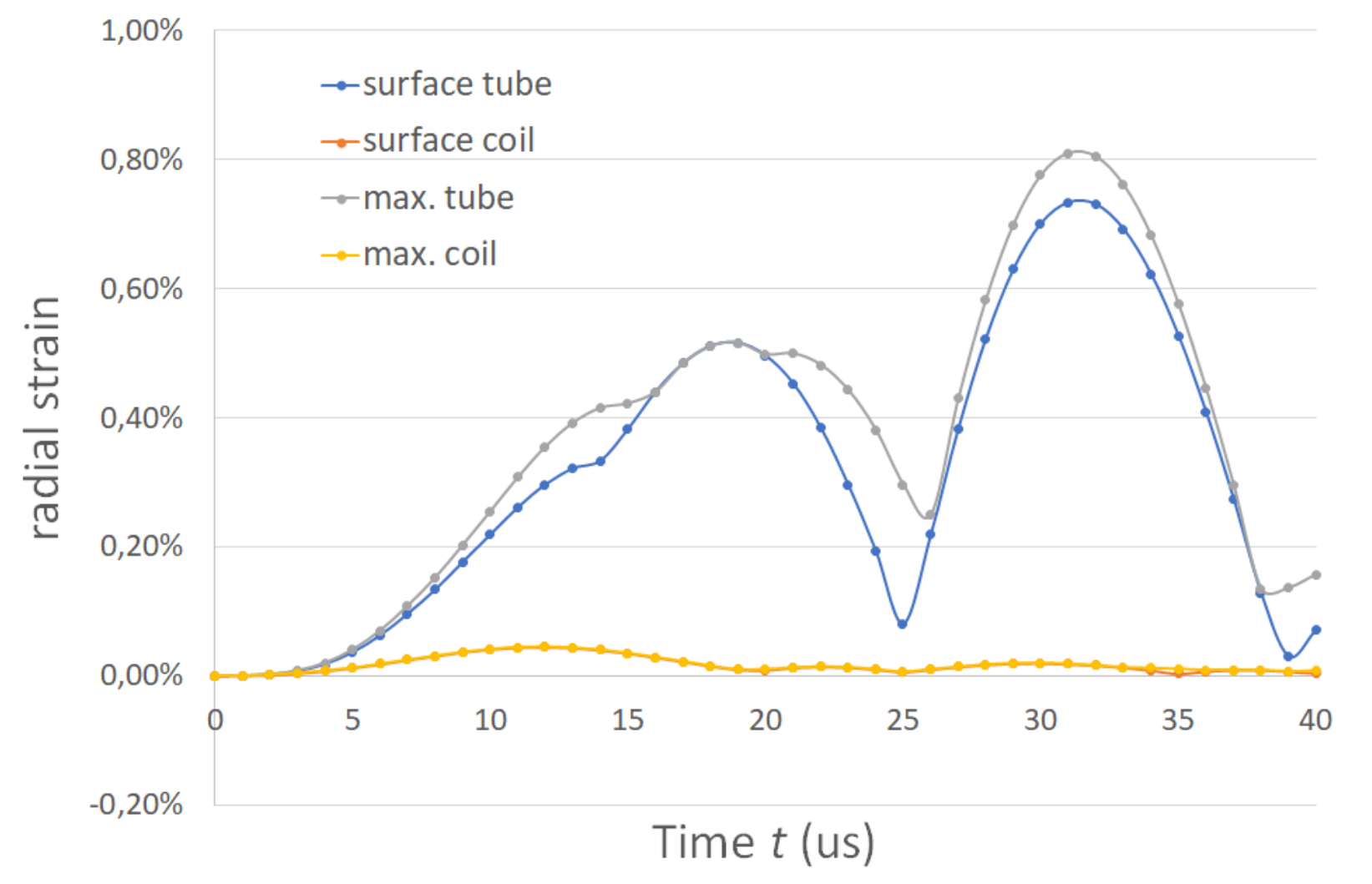


Figure 11. Coil & tube $\varepsilon_{max}(t)$ & $\varepsilon_{surf}(t)$.

Conclusions

Electrical, magnetic, mechanical and thermal physics can be used and coupled to compute single turn coils with a cut dedicated to the pulsed magnetic technologies. It provides useful information for analytical developments, thresholds estimation to achieve plastic deformation, new design, aging analysis and coils and/or system optimizations.

References:

[1] O. Maloberti & al, *COMSOL conference, Grenoble* (2015)
[2] O. Mansouri & al, *ICHSF conference, Dortmund*, (2016)

Excerpt from the Proceedings of the 2018 COMSOL Conference in Lausanne