MATHEMATICAL MODELLING OF THE INDUCTION SOLDERING PROCESS FOR THE COILS CONNECTION

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Abstract - This paper presents the mathematical numerical modeling of the induction soldering process for the connection between coils which can be made only after they are mounted on the magnet already in final form painted and mechanical processed, in order to overcome to the technical difficulties and to optimize the characteristics of the inductor according to the technical requests.

Keywords: Numerical Modeling, Soldering Process, Induction Heating, Finite Element Method, Coils Connection.

1. Introduction

FAIR, the "Facility for Antiproton and Ion Research" is an integrated system of particle accelerators which will provide high energy and high intensity beams of ions from antiprotons to uranium particle, which will be set up in Darmstadt, Germany.

FAIR presented in Fig.1 will give up to physicists and other scientists from Europe and from across the world the possibility to conduct cutting-edge research in fields like physics of the structure of atomic nuclei; physics of nuclear matter under extreme conditions; plasma physics, physics of the atomic shell; related applications [1].

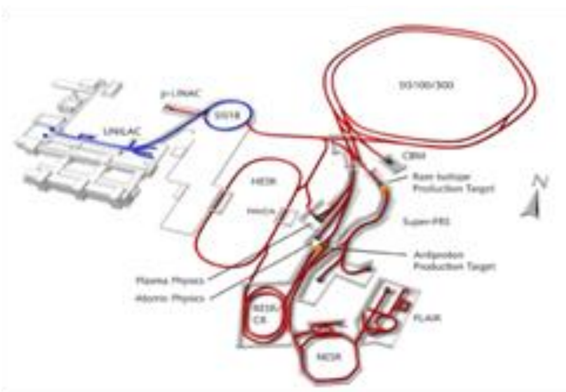

Figure 1: The FAIR complex [1].

Since 2007 ICPE-CA was adopted in the HESR consortium, created to develop the High Energy Storage Ring, important part of the FAIR project [2].

With a circumference of 574 m the HESR presented in Fig. 2 is dedicated to Strong Interaction studies with antiprotons in the momentum range from 1.5 to 15 GeV/c. Powerful phase-space cooling is needed to reach demanding experimental requirements in terms of luminosity and beam quality.

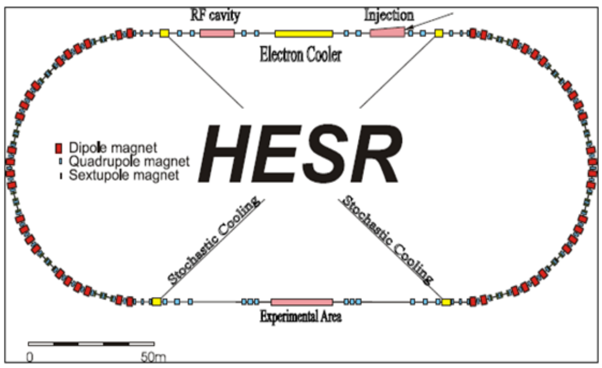

Figure 2: Layout of HESR [2].

The contribution of ICPE-CA to HESR consists, among other equipment, of 66 sextupole magnets, which will be integrated in the storage ring.

The Storage Ring will include 66 normal conducting DC sextupole magnets with a maximum strength of 45 T/m2, an aperture of 140 mm and a magnetic length of 300 mm.

2. The Sextupole Magnet and the Magnetic Inductor

The sextupole magnet presented in Fig. 3 consists of two glued half-yokes, made from 1 mm thick low carbon steel laminations. On each half-yoke are installed three coils with 15 windings each, made from hollow copper conductor with a cross section of 66.77 mm2 and a cooling bore of 4 mm. In Table 1 is presented the characteristics of the Sextupole magnet.

Table 1 Characteristics of the Sextupole Magnet

Parameter	**Sextupole**
d^2B/dx^2	max. 45 T/m^2
Aperture	140 mm
Magnetic length	300 mm
Number of coils	6
Max. current	290 A
Max. weight	~ 400 kg
U_{CC}	6,12 V
R	21,12 mΩ
Inductivity	3,4 mH
Power	1,8 kW

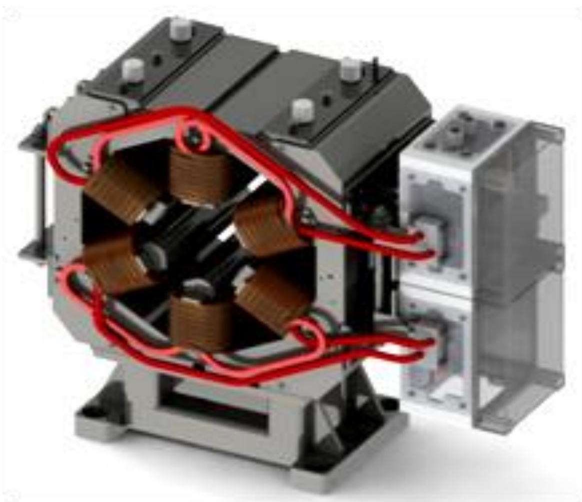

Figure 3: The Sextupole Magnet for HESR – CAD perspective.

Those three coils mounted on the half yoke are connected in a serial arrangement, the connections between the coils being made by induction soldering, using BrazeTec 6009 (Ag 160 according to ISO 17672) with: nominal composition: 60% Ag, 30% Cu, 10% Sn; melting range: 600 – 730 ◦C and working temperature: ~720 ◦C [3]. The connection between coils is presented in Fig. 4.

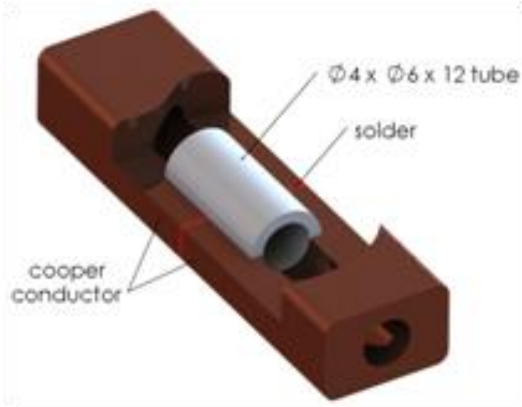

Figure 4: The connection between coils.

The physical mechanisms behind induction soldering are explained by Faraday law of induction which says that any change in the magnetic environment of a coil will cause a voltage (Electromotive force (EMF)) to be induced in the coil. Thus, when an alternating current flows through inductor at a chosen frequency, it will generate a time varying magnetic field around the inductor. When this is placed close to an electrically conductive material, eddy currents [4] are induced in the material. These eddy currents flow against the electrical resistivity of the metal, generating precise and localized heat without any direct contact between the conductive object and the inductor presented in Fig. 5. This heating occurs with both magnetic and non-magnetic parts, and is often referred to as the "Joule effect".

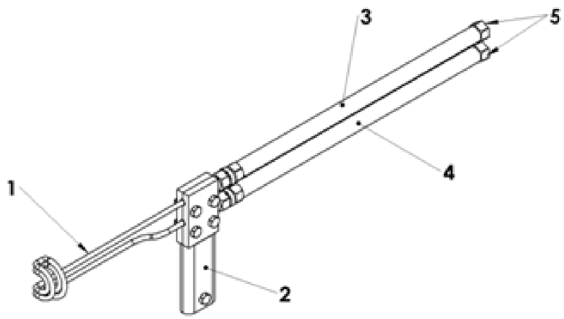

Figure 5: The magnetic inductor: 1 - Copper pipe Ø6xØ4; 2- Handle; 3- Inlet water cooling hose ; 4- Outlet water cooling hose; 5- Connection nuts

Soldering process presents difficulties due to connections between coils that can be made only after they are installed on the magnet yoke, this one being already in final form, including mechanical processing and painting. Because of this, the inductor must have a special U shape and cannot be wrapped completely around the connection, because it could not be extracted after the soldering.

The distance between the connection and the half-yoke is very small (~ 10 mm) and the steel from which the yoke is made is a magnetic material, and this heats easier than non-magnetic materials such as copper, the material of the connected elements.

3. The Mathematical Model

Induction Soldering Process is a time harmonic regime problem characterized by: magnetic flux law, electromagnetic induction law, Ampere law and laws of materials, as in (1).

$$\nabla \mathbf{B} = 0,$$
$$\nabla \times \mathbf{H} = \mathbf{J},$$
$$\mathbf{B} = \mathbf{B}(\mathbf{H}) \rightarrow \mathbf{B} = \mu \mathbf{H} + \mathbf{B}_r,$$
$$\mathbf{J} = \sigma(\mathbf{E}) \rightarrow \mathbf{J} = \sigma \mathbf{E} + \mathbf{J}_i. \quad (1)$$

where:
B [T] - magnetic flux density;
E [V/m] - electric field;
H [A/m] - magnetic field;
J [A/m^2] - current density;
σ [S/m] - electric conductivity;
μ[H/m] - magnetic permeability
Br - residual magnetic flux density;

Numerical modeling of the soldering process was done in Comsol Multiphysics 5.0 software as a coupled problem [5]. The 3D CAD model was designed in SolidWorks 2014 Professional Software [6].

The considered geometry for the problem together with computational domains and materials can be seen in Fig. 6.

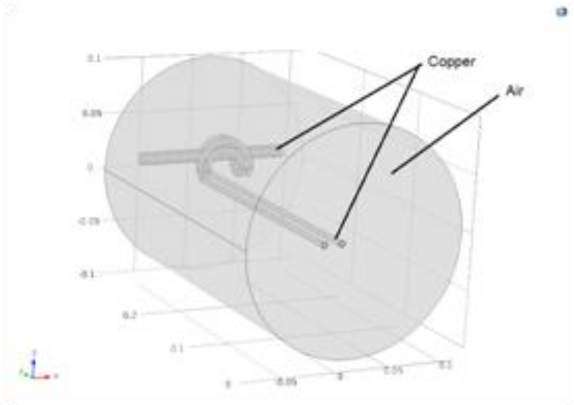

Figure 6: Computational domain and materials.

The voltage of the inductor was set to 250V as in Fig.7 at a frequency of 50kHz . The resistivity of the material (Copper in our case) is temperature dependent according to (2).

$$R = R_{ref}[1 + \alpha(T - T_{ref})] \quad (2)$$

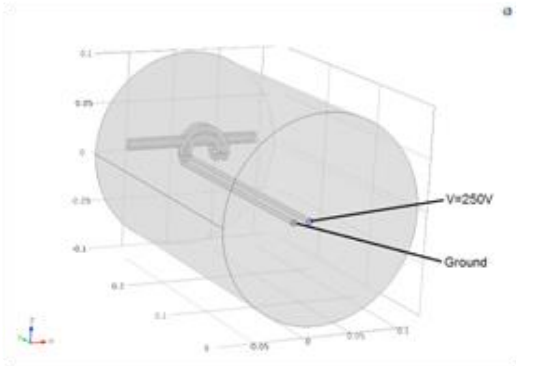

Figure 7: Boundary conditions.

4. Numerical Simulation Results

The FEM mesh for the analyzed 3D model (Fig. 8) consists of approx. 196.227 tetrahedral elements and number of degrees of freedom 1.868.150.

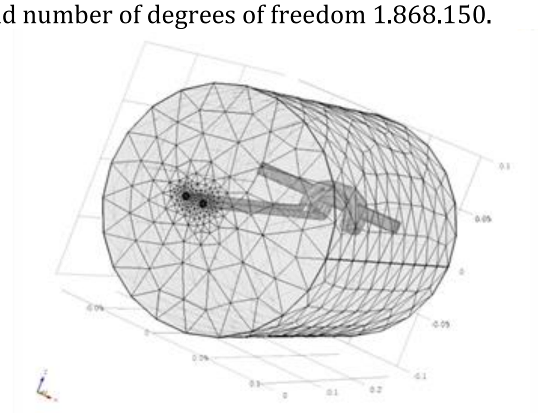

Figure 8: The 3D FEM mesh for the magnetic inductor analyzed

Considering the properties of the soldering alloy mentioned above, the temperature necessary for the soldering process is around 700 C degrees, temperature that was obtained by FEM modeling in 42 seconds using quadratic Lagrange elements and iterative solver BiCGSTAB (Biconjugate Gradient Stabilized Method) preconditioning left as can be seen in Fig. 9.

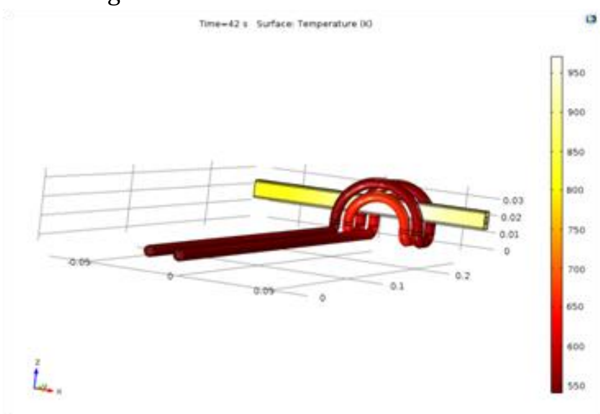

Figure 9: Temperature distribution during the soldering process at 42 s

The induced current density distribution and magnitude can be seen in Fig. 10.

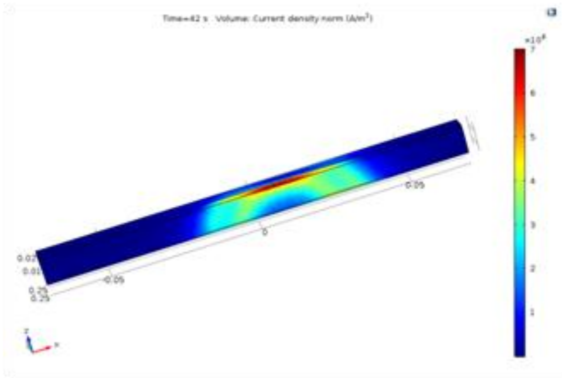

Figure 10: Current density distribution on the copper winding during the soldering process

In Fig. 11 the magnetic flux density streamline is represented and in Fig. 12 its distri-bution. The color is proportional with the local amplitude of the field.

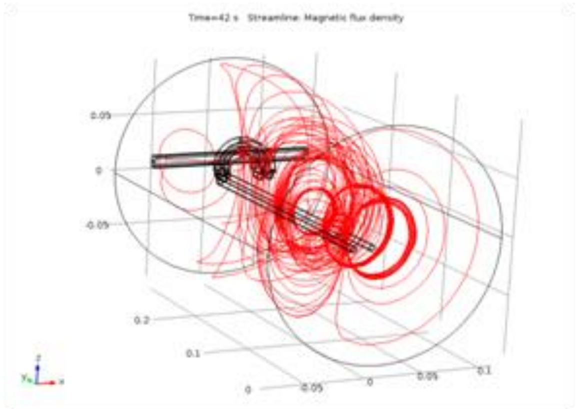

Figure 11: The magnetic flux density streamlines

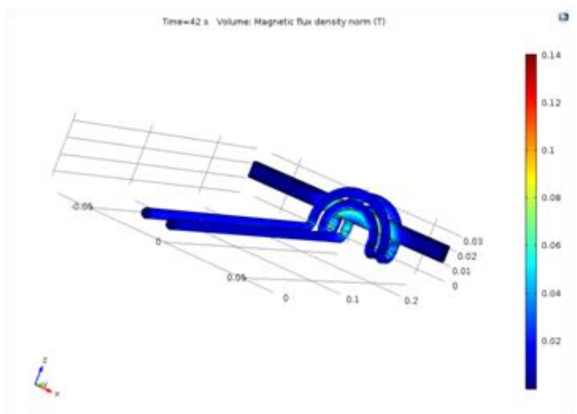

Figure 12: Magnetic flux density distribution.

5. Conclusions

The mathematical numerical modeling of the induction soldering process for the connection between coils was presented. The alloy used in the soldering process requires a temperature of approximately 700 C degrees, so the purpose of the numerical modeling was to identify the geometrical properties and functioning parameters of the inductor that would allow us to obtain in the coils the needed temperature for a successful soldering process.

The results of the numerical modeling indicate that, using the considered above properties of the inductor, the required temperature is reached after 42 seconds.

Acknowledgements

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