EFFECT OF A METALLIZED CHAMBER UPON THE FIELD RESPONSE OF A KICKER MAGNET: SIMULATION RESULTS AND ANALYTICAL CALCULATIONS

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Abstract

Metallized racetrack vacuum chambers will be used in the pulsed magnets of the Austrian cancer therapy and research facility, MedAustron. It is important that the metallization does not unduly degrade field rise and fall times or the flattop of the field pulse in the kicker magnets. This was of particular concern for a tune kicker magnet, which has a specified rise and fall time of 100 ns. The impact of the metallization, upon the transient field response, has been studied using Finite Element Method (FEM) simulations: the dependency of the field response to the metallization thickness and resistivity are presented in this paper and formulae for the field response, for a ramped transient excitation current, are given. An equivalent circuit for the metallization allows the effect of an arbitrary excitation to be studied, with a circuit simulator, and the circuit optimized. Furthermore, results of simulations of the effect of a magnetic brazing collar, located between the ceramic vacuum chamber and flange, of the tune kicker magnet, are reported.

VALIDATION OF FEM PREDICTIONS

The resistivity and thickness of metallization of the vacuum chambers, for the MedAustron kicker magnets, are chosen from 2D FEM simulations and formulae. In order to prove the validity and accuracy of these they are compared with measurements for the LHC dump (MKD) kicker magnet [1]. The MKD and the MedAustron kicker magnets are lumped inductance type magnets.

FEM Simulations

The measured driving current for the MKD was used as an input for the FEM simulations for validating the predictions. The current, predicted and measured fields, for a chamber with an effective titanium coating thickness of 1.833 µm, are plotted in Fig. 1.

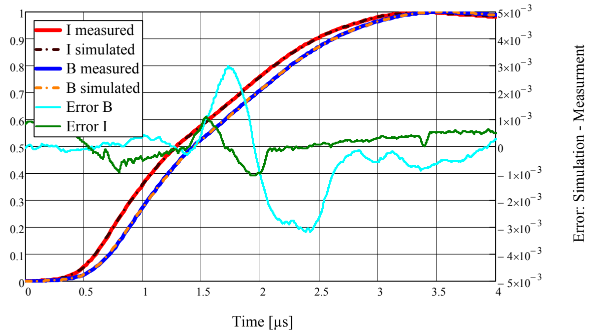

Figure 1: LHC MKD measurements [1] compared with simulation results: the errors between simulations and measurements are shown.

The MKD field is measured along the centreline of the magnet aperture: similarly the predicted field is evaluated at the centre of the aperture of the 2D model. The maximum error between the FEM prediction and the measured magnetic field, evaluated by linear interpolation of the discrete values, is less than 0.4 % (Fig. 1). This maximum error is achieved for all three MKD chambers that were tested, which had effective coating thicknesses, determined by the longitudinal DC resistance, of 1.833 µm, 2.044 µm and 2.344 µm. The good agreement between measurements and predictions confirms that the metallization for the MedAustron kicker magnets can be chosen from FEM simulations.

Additional FEM simulations showed that the same values for field attenuation and field delay are obtained if the coating thickness (d) or the conductivity (σ) of the metallization is changed, provided that both the d.c. resistance, proportional to 1/(σd), is unaltered and that the skin depth is much larger than the coating thickness [4]. Thus the effect of a very thin coating thickness can be modelled using a thicker coating and a proportionately smaller conductivity, without the meshing problems which very thin coatings can cause.

Analytic Calculation

The analytic solution of [3], for the field rise in a metallized chamber, showed a discrepancy with respect to FEM predictions [2, 5] and thus also with respect to the measurements presented above. Thus, herein, the formula of [3] has been adapted with a correction factor. In addition, formulae have been derived for a current ramp excitation (Eqs. 1-4). The new analytic solution is in good agreement with the predictions from the FEM model (Fig. 2).

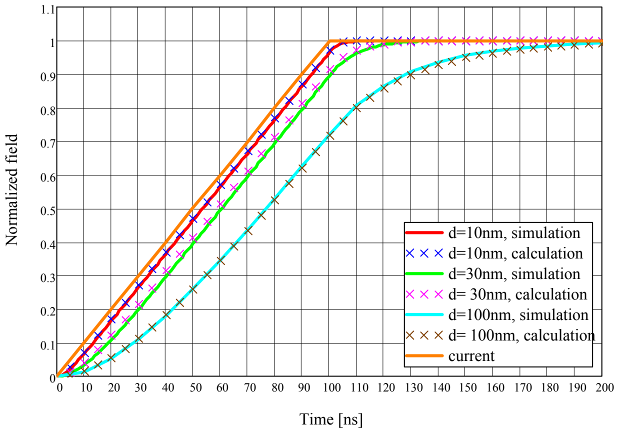

Figure 2: FEM predictions for field compared with new analytic solution (Eq. 1-4) for ramped currents.

$$B_1(t) = B_0 \frac{\tau}{t_{rise}} \left(e^{-\frac{t}{\tau}} + \frac{t}{\tau} - 1\right) \text{, for } t \le t_{rise} \quad (1)$$

$$B_2(t) = B_1(t_{rise}) - B_1(t - t_{rise}) \text{, for } t > t_{rise} \quad (2)$$

$$\tau = \mu_0 \sigma d \Delta_{corr} \quad (3)$$

$$\Delta_{corr} = k_1 w^{1.995} + k_2 h^{1.646} - k_3 \quad (4)$$

Where:

B_0 = maximum applied field [T]

B_1, B_2 = magnetic field at centre of vacuum chamber [T]

t_{rise} = rise time of the ramped current [s]

τ = time constant, including correction factor [s]

μ_0 = permeability of free space [H/m]

σ = coating conductivity [S/m]

d = equivalent coating thickness [m]

w = inside width of ceramic chamber metallization [m] (width is defined to be orthogonal to the direction of the magnetic field)

h = inside height of ceramic chamber metallization [m] (height is defined to be in the direction of the magnetic field)

Δ_{corr} = correction factor, from FEM simulations [m]

k_1 = constant (3.498) [$m^{-0.995}$]

k_2 = constant (1.3) [$m^{-0.646}$]

k_3 = constant (2.97E-3) [m]

Eqs. 1-3 can be used for round and racetrack chambers. The correction factor (Eq. 4) is dependent on the geometry of the vacuum chamber: for round chambers the width and the height are both set equal to the diameter of the metallization.

Equivalent Electrical Model

The time constant (Eq. 3) can be simulated electrically as a parallel resistor and inductor (L). The value of L corresponds to the inductance of the magnet without a metallized chamber, while the resistance is calculated from L/τ, where τ is the time constant determined from Eq. 3 and 4. The current through the inductor is equivalent to the magnetic field at the centre of the metallized vacuum chamber. The predictions from this equivalent circuit, not presented here, are identical to the analytic solution: the advantage of the equivalent circuit is that it can be excited with an arbitrary shaped waveform. Hence PSpice simulations of the complete kicker system, including vacuum chamber metallization, can be used to optimize and achieve minimum field transition times by tuning current overshoot and thus partially compensating for the field attenuation and delay introduced by the metallization.

APPLICATION TO MEDAUSTRON

The FEM models and formulae for a metallized ceramic vacuum chamber have been used to choose the coating thickness and resistivity of the MedAustron tune kicker magnet (Fig. 3).

Choice of Metallization Properties

Fig. 4 is derived from Eq. 1 and 2: the graph is for a racetrack chamber of 145 (w) × 74mm (h) and a ramped current. Fig. 4 can be used for various current rise times, coating thicknesses and material conductivities.

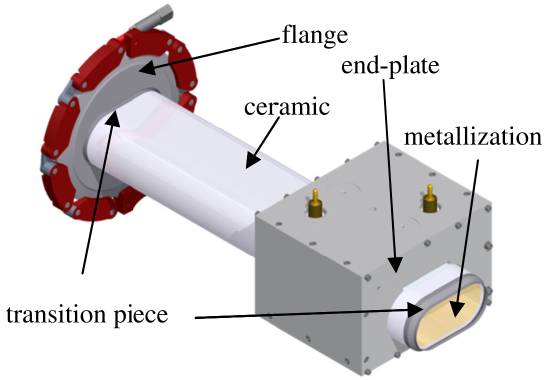

Figure 3: MedAustron tune kicker magnet with ceramic racetrack chamber and titanium coating.

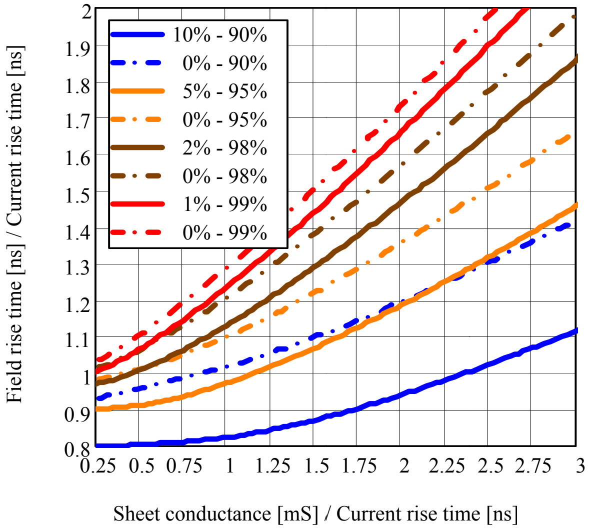

Figure 4: Field rise time versus sheet conductance: note that the field rise time and sheet conductance are both normalized to the current rise time.

The following is an example of the application of Fig. 4: for a current ramp rise time of 100 ns, both coordinate axes are multiplied by 100. Thus, for a required field rise time of approximately 110 ns (0% to 95%) a sheet conductance of 100 mS $\left({}^{\sigma d}/_{t_{rise}} = 1\, mS/ns\right)$, which corresponds to an effective titanium (Ti) coating thickness of 40 nm (Eq. 5), is needed.

Fig. 5 is derived from Eqs. 3 and 4. The blue curve (f=1) shows the dimensions which have the same time constant as the 145 mm (w) × 74 mm (h) chamber of Fig. 4: thus a chamber of 150 mm (w) × 60 mm (h) gives equivalent, normalized, field rise time and sheet conductance results. For chambers with dimensions on the red (f=2) or green (f=0.5) curves (Fig. 5) the x-axis of Fig. 4 has to be multiplied by 2 or 0.5, respectively.

The metallization thickness calculated is an effective value and, as a result of surface roughness and imperfections, is generally different from the actual thickness. Hence for the manufacture of the metallized chamber, the required sheet resistance of the coating (Eq. 5) [4, 6] is specified:

$$R_{sheet} = \frac{1}{\sigma d} \qquad (5)$$

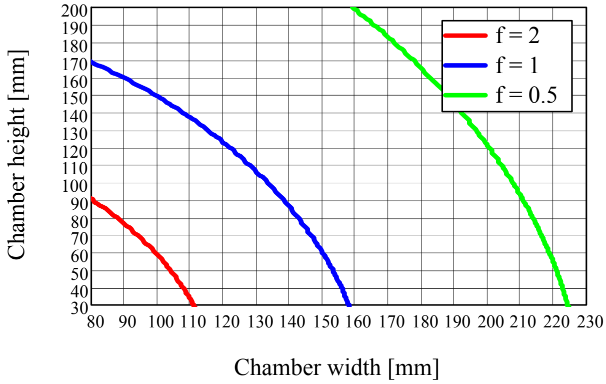

Figure 5: Diagram to extend the use of Fig. 4.

The reciprocal of Eq. 5, the sheet conductance, is used on the x-axis of Fig. 4. Hence for a current rise time of 100 ns the x-axis of Fig. 4 starts with a sheet conductance of 25 mS: this corresponds to an effective Ti metallization thickness of 10 nm.

Improvement of the Field Rise Time

The tune kicker has the shortest transition times of the MedAustron kickers and has thus been studied in detail. This kicker system has been modelled, using PSpice, together with the equivalent electrical model of the power converter, magnet and metallized chamber. The value of a capacitor, on the input of the tune kicker magnet, has been used to optimize the rise time and overshoot of the magnet field.

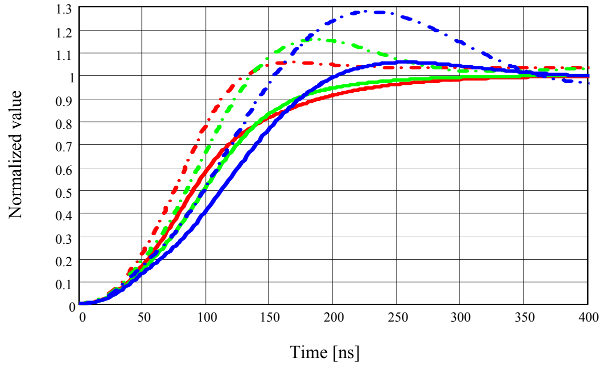

Figure 6: Normalized driving current (dashed) and magnetic field (solid) for different input capacitances.

In Fig. 6 the dashed lines represent the predicted driving current for the tune kicker, while the predicted field is indicated with solid lines. The optimum capacitor value is chosen dependent on both the required field rise time and the permissible field overshoot.

VACUUM CHAMBER LENGTH

2D models do not take into account the ends of the vacuum chambers, which are equipped with nonmagnetic flanges brazed to the ceramic chamber via magnetic transition pieces. To determine an appropriate length of the ceramic chamber, so as to not unduly influence the effective magnetic length of the magnet, 3D d.c. FEM simulations for a MKC magnet [7] have been carried out to study the effect of the distance between the endplate and magnetic transition piece: eddy currents are neglected.

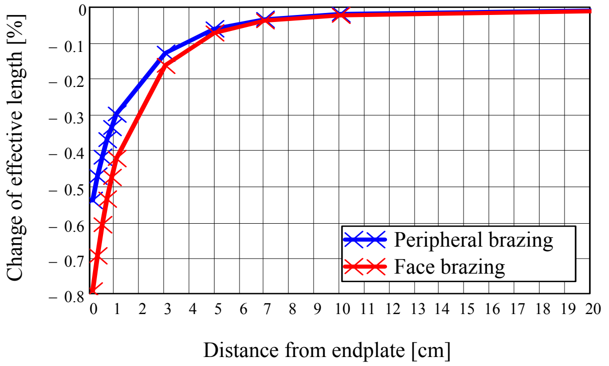

Figure 7: Relative change of effective length over distance of brazing to endplate of magnet for peripheral and face brazed flanges.

The effective length of the MKC is approx. 300 mm. Since the brazing only influences the end fields, the effect will increase for shorter magnets and decrease for longer ones. By keeping a distance of 3 mm between transition piece and end plate, the effective length will be reduced by 0.7 % (Fig. 7) in the worst case.

CONCLUSIONS

FEM simulations of the transient field inside metallized ceramic chambers show good agreement with 3 different measurements. An existing formula has been developed to be used with ramped currents and, with the help of FEM simulations, adapted with a correction factor to be more accurate. The simulations and the analytic formulae are in good agreement with each other. The time-constant for a metallized ceramic, obtained from formulae, has been incorporated in a PSpice model of the kicker system so that arbitrary excitation waveforms can be considered and the system optimized for the magnetic field rise and fall times.

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