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MULTIPHYSICS SIMULATIONS OF IMPEDANCE EFFECTS IN ACCELERATORS

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Abstract

Multiphysics is a computational discipline that involves multiple physical models. Nowadays commercial 3D simulation codes allow to couple electromagnetic and thermo-mechanical effects. Considering all the induced effects of the electromagnetic fields is fundamental in the development of electromagnetic devices. In this paper, the importance of Multiphysics simulations applied to beam coupling impedance is discussed.

INTRODUCTION

The input power of an electromagnetic device (RF components, accelerator elements etc.) will be partially or almost completely dissipated in the device walls. A good estimation of the power that needs to be dissipated in the device and of its distribution is fundamental to avoid unexpected failures of the component due to thermal and/or structural effects induced by the electromagnetic fields (EM fields). Figure 1 shows the Multiphysics design loop. First, the EM fields and the surface power loss density map are obtained as output of the electromagnetic simulation. Therefore, the power loss density map is used as input of a thermal simulation which will give as main output a thermal map of the device. This map can be used as input of structural simulations to estimate the induced mechanical stress and the structural deformation of the device. Finally, the deformed mesh can be imported in the electromagnetic simulations to study the effect on the EM fields. Performing the design loop illustrated in Fig. 1, EM fields induced thermo-mechanical issues (excessive heating, mechanical stress close to the ultimate tensile strength of the material, unacceptable frequency shift due to wall deformation) could be predicted and corrective actions in the design could be taken at an early stage.

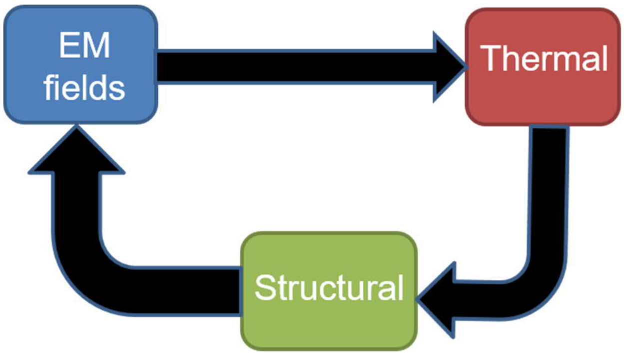

Figure 1: Multiphysics design loop for electromagnetic components

MULTIPHYSICS SIMULATION APPLIED TO IMPEDANCE EFFECTS

The beam coupling impedance characterizes the interaction between the particle beam and the accelerator devices. During the traversal through the accelerator, the particle beam will induce electromagnetic fields which will affect the motion of the beam itself. This mechanism is studied to understand, predict and prevent the beam instability behaviour. However, beam induced EM fields are also responsible of induced effects on the accelerator device itself (heating and structural deformation) which could lead to a modification of the induced EM fields. In order to study also these effects, the Multiphysics design loop has to be applied to beam coupling impedance simulations. Figure 2 shows the Multiphysics design loop detailed for beam coupling impedance studies. In the following, I will describe how to perform the design loop of Fig. 2 by using the commercial simulation package CST Studio Suite [1].

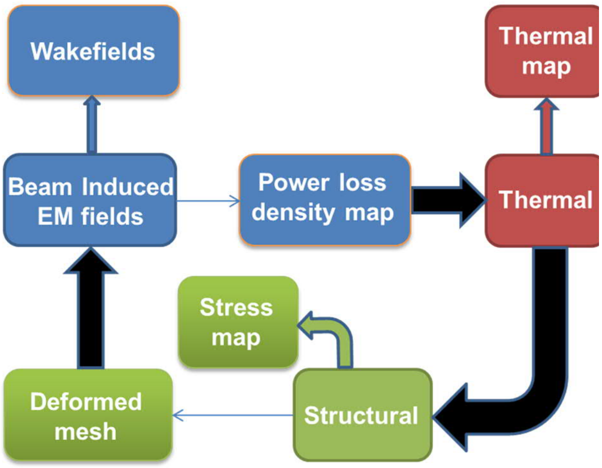

Figure 2: Multiphysics design loop for beam coupling impedance simulations

The first step consists in the computation of the beam induced EM fields. These fields could be calculated performing eigenmode, frequency domain or time domain calculations. The eigenmode would be more appropriate for the simulation of resonating structures (RF cavities and cavity like structures), the frequency domain would fit better for complex devices where the discretization of the domain of calculus requires the use of tetrahedral meshes while time domain simulations (scattering matrix and/or wakefields) could be accurately performed when hexahedral meshes can be used for an accurate representation of the calculus domain. Post-processing eigenmode, frequency domain and time domain results or as direct output of the wakefield

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solver is possible to get the wake function and its representation in the frequency domain: the beam coupling impedance.

In the eigenmode simulations, the longitudinal and transverse impedances are reconstructed by using the broadband resonator formulae [2]:

$$Z_{\parallel}(f)=\frac{R}{1+jQ\left(\frac{f}{f_r}-\frac{f_r}{f}\right)} \tag{1}$$

$$Z_{\perp}(f)=\frac{f_r}{f}\frac{R_{\perp}}{1+jQ\left(\frac{f}{f_r}-\frac{f_r}{f}\right)} \tag{2}$$

The linear terms of the transverse impedance (dipolar and quadrupolar) can be obtained from the generalized (parabolic) longitudinal impedance using the Panofsky-Wenzel theorem [3].

In the frequency domain simulation, the beam coupling impedance can also be obtained by integrating the electric field at each frequency according to its definition or from the scattering parameters derived by simulating the coaxial wire method setup [4, 5, 6]. In the time domain, the impedance can be obtained from the scattering matrix as for the frequency domain. The time domain wakefield solver gives directly as output result the beam coupling impedance, which is calculated from the wake potential applying the convolution theorem.

A power loss density map can be exported from the EM fields distribution and used as input of thermal simulations. The simulated total power loss can be normalized to the beam induced power loss by using the following normalization factor:

$$Nfactor=\frac{\Delta W}{\Delta W_{sim}} \tag{3}$$

where ΔW is the beam induced power loss obtained considering the actual beam spectrum [7, 8] and ΔW_{sim} is the simulated power loss.

After an accurate definition of the thermal material properties and boundary conditions thermal simulations can be performed. The output of these simulations will give all the information about the thermal behaviour of the device when exposed to the simulated beam induced EM fields. This allows identifying hot spots and driving design modifications and cooling efficiency optimization. The thermal map can be used as input for structural simulations. After an accurate definition of mechanical material properties and boundary conditions structural simulations can be performed. The output of the mechanical simulations will depict the structural behaviour of the device in the presence of the simulated beam induced EM fields. This allows identifying critical points, possible breaking points and modifying design accordingly. Structural simulations also allow exporting the deformed mesh which could be then used to simulate the deviation of the induced EM fields and therefore of the beam coupling impedance caused by the structural deformation of the accelerator component. The modified beam induced fields could then be used as input for a new loop. Ideally, the Multiphysics design loop should be performed iteratively to find the steady state behaviour of the device under study. However, usually the deviation of the beam induced fields leads to negligible effects on the thermo-mechanical behaviour of the accelerator element.

EXAMPLES OF APPLICATION

In this section some examples of application will be presented to underline the importance of the Multiphysics design loop for beam coupling impedance studies.

CERN-SPS extraction kicker

The CERN-SPS extraction kicker consists of a C-shaped ferrite magnet. After the installation in the machine, it was realized that this accelerator component was suffering of excessive beam induced heating [9]. Therefore, it was needed to introduce a modification to reduce the beam induced heating of this device. Silver paste was used to print by serigraphy finger pattern directly on the ferrite to reduce the beam coupling impedance and consequently the beam induced heating [10] (see Fig. 3).

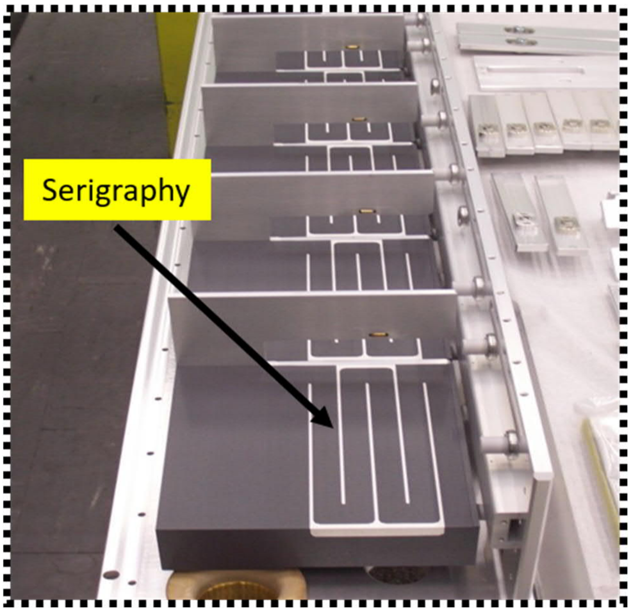

Figure 3: Top view of the serigraphed CERN-SPS extraction kicker ferrite magnet.

Having, the Multiphysics design in place would allow identifying similar issues in the design phase and taking the corrective actions at the design stage. Moreover, the Multiphysics design loop gives an extensive picture of the beam induced EM fields induced effects and therefore, it gives all the elements to the designer to implement the best solution. For example, in the specific case of the SPS extraction kicker the solution implemented gives a significant improvement with respect to the original design but is not optimized in terms of beam induced heating. An additional significant improvement could be obtained optimizing the serigraphy length. The serigraphy introduces a λ/4 resonance on the finger length [7] (see Fig. 4). To minimize the impact of this resonance on the beam induced heating the finger length could be optimized to shift the resonance frequency as far as possible from the beam spectrum lines. A resonant frequency of about 50 MHz has been considered an appropriate choice in order to have a workable solution for both 25 ns and 50 ns bunch spacing particle beam (see Fig. 5). This required shortening the serigraphy length by 20 mm. The solution has been implemented and experimentally validated during SPS scrubbing runs [11].

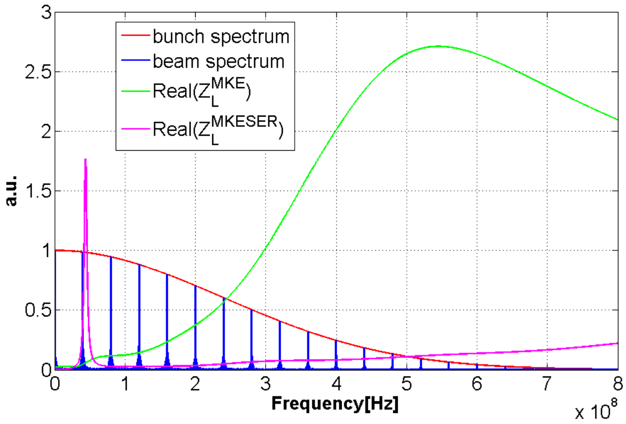

Figure 4: Beam coupling impedance of the CERN-SPS extraction kicker with (magenta curve) and without (green curve) serigraphy. CERN-SPS beam and bunch spectrum are also shown for the beam with 25 ns bunch spacing.

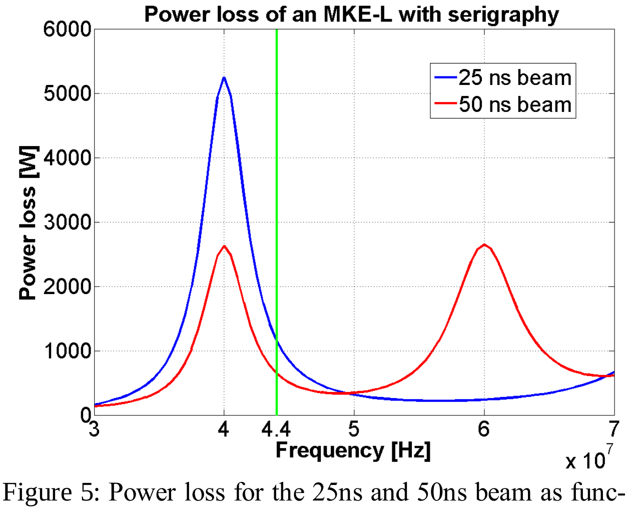

Figure 5: Power loss for the 25ns and 50ns beam as function of the frequency of the resonance introduced by the serigraphy. The green line corresponds to the resonant frequency of the original serigraphy.

The CERN-SPS extraction kicker is just a possible example of application. The Multiphysics design loop should ideally be applied to each accelerator component exposed to the particle beam. The correct implementation of the Multiphysics design loop would allow having more efficient solution and will give us a better understanding of the observed thermal and structural behaviour. For instance, it would allow understanding if wire breaking in the wire scanner could be related to beam induced heating. Finally, the author would also like to stress the importance of performing the full Multiphysics design loop including the structural simulations. In fact, critical structural deformation which could bring to serious damage and/or rupture does not require having an enormous heating. In particular situations, 5-6 °C of heating could cause serious damage to the accelerator element.

COMPONENT DESIGN FLOW PROCESS

In this last section the author would like to suggest a possible implementation of the Multiphysics design loop for beam coupling impedance in the design of new accelerator elements. A flow chart is displayed in Fig. 6. The design ownership of new devices should be assigned according to the functionality of the accelerator component. Once a functional design is ready, the impedance team could perform a first check looking at all the impedance induced effects. This would require the implementation of the Multiphysics design loop in collaboration with thermal and mechanical engineers for the thermal and structural simulations. If modifications are needed, they will be submitted to the owner of the design for the implementation in the functional design. Once a functional design is approved, the design team can work on the detailed design, which will be checked again by the beam coupling impedance team, which will eventually consider the design impedance compliant or will require additional modifications. Identifying possible impedance issues at an early stage in the design phase will pave the way to have optimized design in terms of beam coupling impedance and its induced effects.

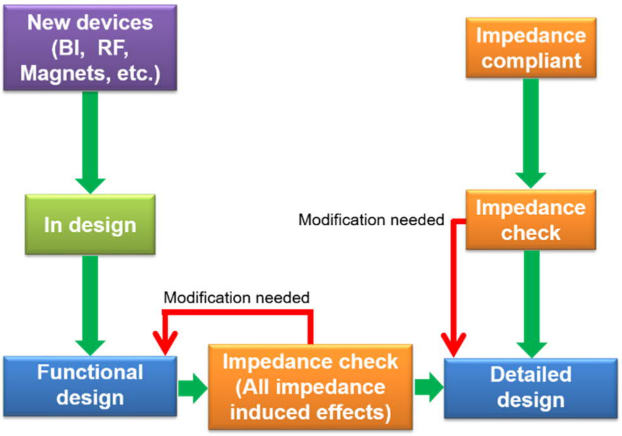

Figure 6: Flow chart for the design of an accelerator component: beam coupling impedance perspective.

SUMMARY

The Multiphysics design loop applied to beam coupling impedance studies has been presented. The implementation of the design loop by using CST Studio Suite has been discussed. The importance of these simulations has been emphasized giving specific examples. Finally, the implementation of the Multiphysics design loop for beam coupling impedance studies in the design of new accelerator elements has been also discussed.

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