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SIMULATION OF THE THERMAL DEFORMATION AND THE COOLING OF A FOUR-ROD RADIO FREQUENCY QUADRUPOLE*

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Abstract

This paper reports about coupled electromagnetic, fluid-dynamic, thermal and structural dynamic field simulations carried out for predicting the mechanical deformation of the stems and the rods of the four-rod RFQ planned for the MYRRHA proton accelerator.

INTRODUCTION

A four-rod radio frequency quadrupole (RFQ) is used as an initial accelerating component in the proton LINAC for the Multi-purpose hYbrid Research Reactor for High-tech Applications (MYRRHA) at the Belgian Nuclear Research Centre (SCK·CEN) in Mol, Belgium [1, 2]. The RFQ contains four modulated rods kept in place by a number of stems and fixed within a cavity [3, 4]. The RFQ is tuned by appropriately positioning the tuning plates between the stems. The position and the modulation of the rods determine the focusing and accelerating properties of the RFQ. The resonating field induces currents, and by that, Joule losses in the stems, rods and tuning plates. The temperature increase causes a mechanical deformation which may lead to a deteriorated performance of the RFQ. The temperature increase is kept small by cooling the rods, stems and tuning plates.

The prediction of the thermally induced deformations is not straightforward and needs a carefully conceived field scheme involving electromagnetic-field, fluid-dynamics, thermal and structural-dynamics simulations. Such simulations have been carried out for four-vane RFQs in e.g. [5, 6]. A similar calculation for a four-rod RFQ is particularly challenging because of the 3D nature of all involved field phenomena [7].

COUPLED SIMULATION APPROACH

Workflow and Electromagnetic Model

The stems, rods and base plate are modelled in CST MICROWAVE STUDIO® [8]. This model is used to calculate the eigenmodes and the corresponding surface current densities (Fig. 1). The current densities are high at the lower parts of the rods and the stem surfaces. Particular attention is paid to the modelling of the corner parts and the transitions to the rods and the base plate. The geometry and the current densities are exported in a SAT-file and imported in ANSYS

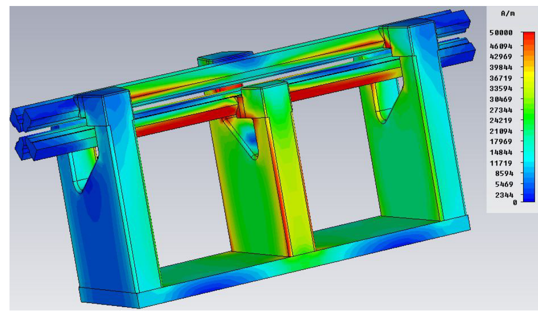

Figure 1: Surface current densities at the copper rods, the stems and the base plate.

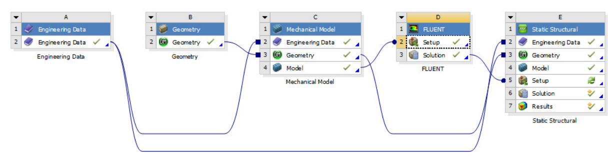

Figure 2: Workflow ANSYS Workbench Platform.

Workbench Platform [9]. There, the fluid-dynamics, thermal and structural-dynamics solvers need to be combined in a particular order (Fig. 2). The fluid-dynamics and thermal solutions are obtained simultaneously, but are iterated starting from a first fluid-dynamics field solution. The temperature distribution is then exported to the structural-dynamics module to calculate the deformations.

Fluid-Dynamics and Thermal Model

The nature of the fluid flow in the cooling channels is determined by the viscosity of the cooling fluid, the size of the channels and the flow speed [10]. The decision whether the flow is laminar or turbulent is based on an estimation of the Reynolds number

$$Re = \frac{u D_H \rho}{\mu} \qquad (1)$$

with u the average fluid speed, $D_H = 4A/P$ the hydraulic diameter, A the pipe cross-section, P the wetted diameter, ρ the fluid density and μ the dynamic viscosity. The Reynolds number for water with a speed of 3 m/s and a dynamic viscosity of 1.002 g/(s·m) through a pipe with cross-section 5×3 mm^2 is 11000, which indicates that a turbulent flow is expected. The fluid flow is calculated by ANSYS Fluent [11] using the standard k-ϵ turbulence model (Fig. 3a). Only a turbulent flow is able to provide a sufficient cooling efficiency. For an inlet water temperature of 10°C and

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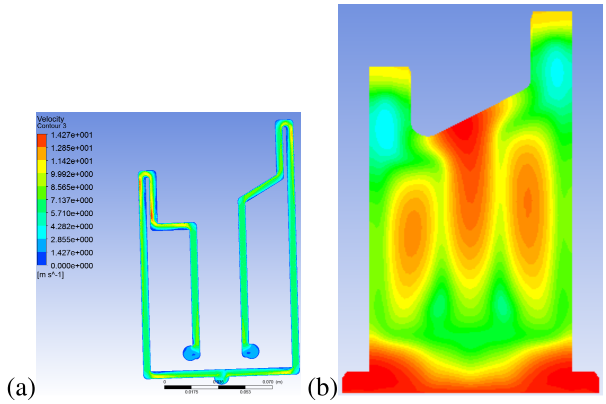

Figure 3: (a) Water velocity in the cooling channel for a water speed of 3 m/s at the inlet; (b) Temperature distribution.

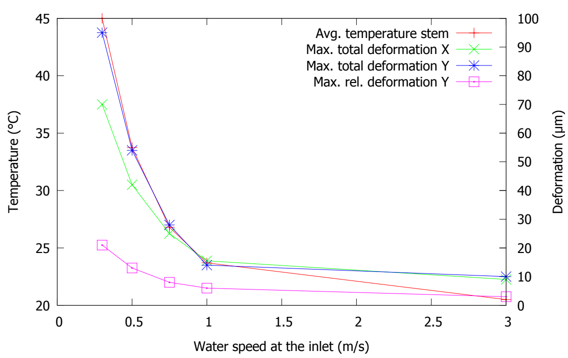

Figure 4: Temperature and deformation of the stem as a function of the inlet speed of the water (turbulent flow).

speed of 4 m/s, the maximal temperature in the stem is 41°C (Fig. 3b). The average temperature of the stem as a function of the inlet water speed is plotted as a red line in Fig. 4. A substantial decrease of the temperature is observed for fluid speeds increasing up to 1 m/s. From then on, the average temperature only decreases moderately.

Structural-Dynamics Model

The calculated temperature distribution serves as an input to the structural-dynamics module of ANSYS. For an inlet water speed beyond 1 m/s, the deformations are less than 20 μm (Fig. 4).

DEFORMATION OF THE RODS

The performance of the RFQ is closely related to the accuracy of the shape and the positions of the rods. It is obvious that any deformation, either during construction or due to thermal heating during operation, will influence the performance of the RFQ and will need to be characterised when not prevented. A possible design of the rod cooling system is shown in Fig. 5. The cooling channels for the rods are independent from the ones for the stems. The same simulation procedure is carried out. The temperature for an inlet water speed of 1 m/s is shown in Fig. 6. Figure 7 shows

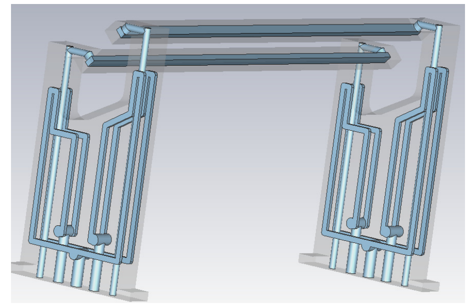

Figure 5: Model of a stem pair connected to each other by two water cooled rods. The are four circuits visible. Two circuits to cool the stems and two circuits to cool the rods.

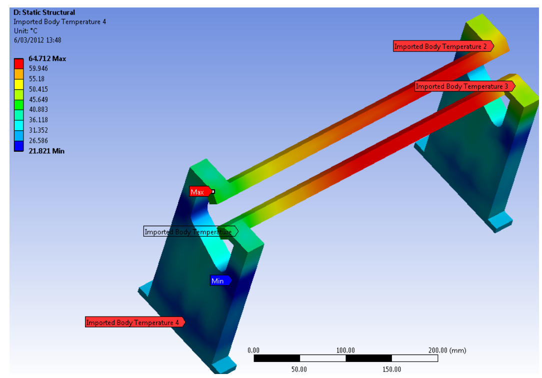

Figure 6: Temperature of the system. Power load: $1e7$ W/m^3 for the stem and $2e7$ W/m^3 for the rods. The water inlet speed is 1 m/s.

the deformation of the rods in case of perfectly stiff stems. The rods bend with a maximal (unacceptable) deformation of 216 μm.

Figure 8 shows an improved design where each stem-rod connection is equiped with both an inlet and an outlet water channel. The temperature distribution is shown in Fig. 9 for an inlet water speed of 3 m/s. The deformations of the rods are shown in Fig. 10. The rods bend towards each other in the horizontal direction, each by less than 10 μm. They are lifted by approximately 20 μm in the vertical plane.

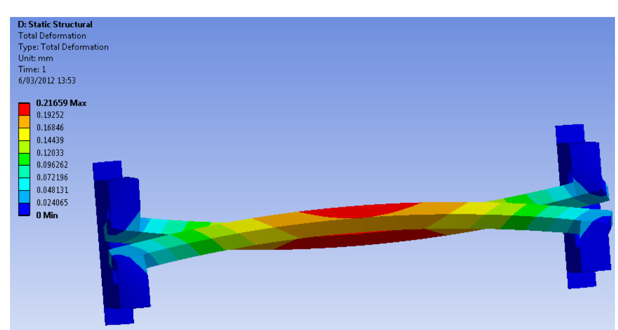

Figure 7: Deformation of the system for fixed stems. This situation will occur in the centre of the RFQ accelerator.

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°C

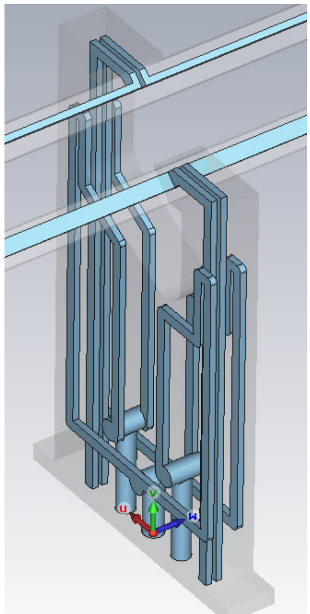


Figure 8: CST model of an RFQ stem with two cooling channels per rod (in and out).

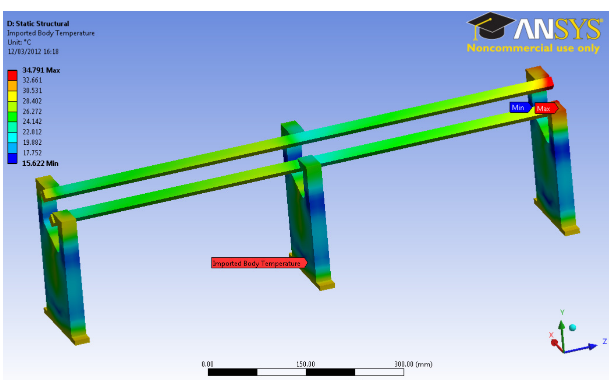
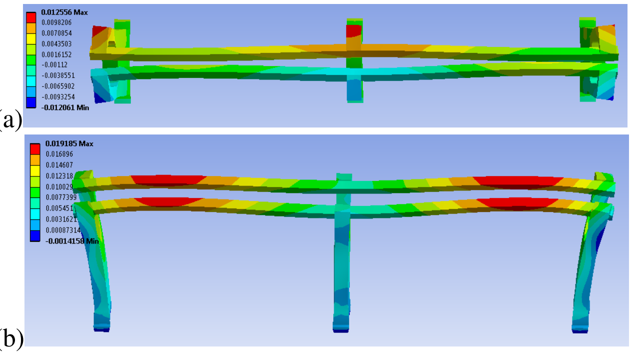


Figure 9: Temperature distribution in the 3-stem model with split cooling channels to the rods.

CONCLUSIONS

The deformations of the stems and rods of a four-rod RFQ due to thermal heating can be predicted by a coupled electromagnetic-field, fluid-dynamics, thermal, structural-dynamics solver. Of major concern are the rods, bending 20 μm towards each other in the horizontal plane and the lifted 20 μm upwards in the vertical plane.

(a)



(b)

Figure 10: (a) Horizontal (up and down in the image) and (b) vertical deformation of the rods.

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