FERMI@ELETTRA LOW-ENERGY RF DEFLECTOR FEM ANALYSIS

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Abstract

FERMI@Elettra is a soft X-ray fourth generation light source under construction at Sincrotrone Trieste SCpA, ELETTRA laboratory. To characterize the beam phase space by means of measurements of the bunch length and of the transverse slice emittance, two deflecting cavities will be positioned at two points in the linac. One will be placed at 250 MeV (Low-Energy RF Deflector), after the first bunch compressor (BC1); the second one at 1.2 GeV (High-Energy RF Deflector), just before the FEL process starts. The Low-Energy RF Deflector consists of 5 cells, standing wave, normal conducting, RF copper cavity. A single Ansys model has been developed to perform all of the calculations in a multi-step process. In this paper we discuss and report on the results of the electromagnetic, thermal, and structural coupled analysis.

INTRODUCTION

Deflectors are diagnostic devices aimed to characterize the electron beam by means of measurements of the bunch length and of the transverse slice emittance [1]. This characterization is one of the most important tasks to perform in order to guarantee the good performances of the FEL process. The FERMI@Elettra layout includes two RF deflecting cavities, working at a different beam energy [1, 2]. The former is the Low Energy RF Deflector (LERFD), that is placed downstream (in respect to the electron beam direction) of the Bunch Compressor 1. The low-energy deflector has been already installed and it is now under conditioning and commissioning. The latter, at 1.2 GeV, is the High Energy RF Deflector that is placed at the end of the linac and it is now under construction. It will be installed during the summer of 2010.

The LERFD will work at a maximum beam energy of 250 MeV and with a S-band RF frequency of 2998 MHz (the operating frequency of the linac). The RF and mechanical design starts from the deflecting cavity developed by LNF-INFN for the SPARC project [3] and then it has been updated in order to match the FERMI@Elettra specifications and requirements.

The low energy deflector is made up of 5 cells, normal conducting, SW, and copper cavity. Fig. 1 and Tab. 1 summarize the main RF and structure parameters.

The FEM analysis performed by Ansys starts with the import of the geometry created by means of SolidWorks, while the simulation provides the cavity natural frequency and H and E distribution inside the cavity, after that it gets the thermal load distribution on the inner copper surface based on H field distribution, evaluates mechanical deformation due to the thermal load, and finally with a mesh-morphing operation evaluates the working frequency shift. The analysis is performed on the basic cell. Taking advantage of the geometry and loads symmetry we have taken onto account only a quarter of the basic cell.

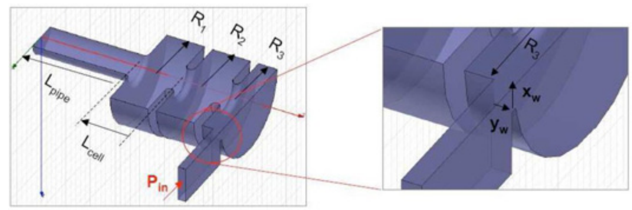

Figure 1: Schematic view of a quarter of the deflector

Table 1: Main geometric and RF deflector parameters

L_{cell}	50 [mm]	f_{RF}	2.998 [GHz]
R_1	58.25 [mm]	Q	15600
R_2	57.6 [mm]	$R\perp$	2.4 [MΩ]
R_3	57.45[mm]	P_{diss}	150 [W]
a	18 [mm]	τ	0.8 [μs]
x_w	8 [mm]	V⊥@5[MW]	4.9 [MV]
y_w	19.5 [mm]		
t	9.5 [mm]		

HIGH FREQUENCY ANALYSIS

The initial step of the analysis has been the high frequency electromagnetic analysis of the volume contained in the cavity. This volume has to be meshed and the boundary conditions have to be applied on the areas that surround the cavity. The permittivity and permeability of the resonating material, in our case vacuum, have been set up obviously to value 1 (as ratio).

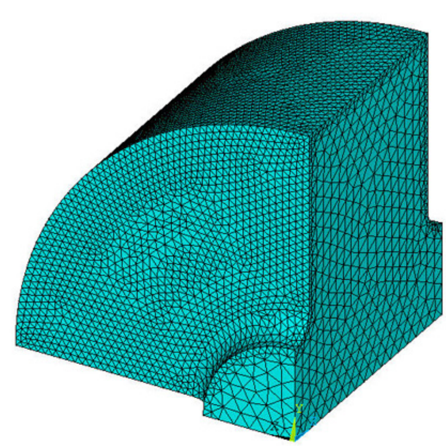

Figure 2: Vacuum volume mesh

The result accuracy is dependent to the mesh quality: the best trade-off between result accuracy and CPU time, and memory usage has to be found. Fine mesh has been created on the copper surfaces while a larger mesh in the body. Fig. 2 shows the vacuum volume mesh: we have meshed the volume using 1.5 mm as the average dimension of each element, and we have performed an area mesh refinement (level 1) on the elements that belong to the external surfaces. We have used first order tetrahedral RF elements (HF119).

A mesh sensitivity analysis has been carried out in order to verify the electromagnetic results variation versus the mesh size. As the figure of merit of the electromagnetic results, we have chosen the cavity natural frequency *f*, the quality factor *Q* and the shunt resistance R_t. The shunt resistance for *n* cells cavity is given by:

$$R_t = \frac{Q|V_t|}{2\omega n U}[\Omega] \qquad (1)$$

where $V\perp$ is the total transverse voltage of the deflecting cavity, Q is the quality factor, ω is the frequency and U is the stored energy of the electromagnetic field.

Tab. 2 summarizes the results for the single basic cell: the mesh size variation does not cause so huge electromagnetic quantities variation, but for thermal simulation and near areas with high field gradient (iris) the mesh size plays an important rule.

Table 2: Electromagnetic quantity vs. mesh size

Element size [mm]	*f* [MHz]	*Q*	R_t [Ω]
3.5	2997.65	14878	438023
3	2997.69	14832	421779
2.5	2997.91	15149	441891
2	2998.13	15376	459107
1.8	2998.12	15338	462470
1.5	2998.10	15350	465645

The electric wall boundary condition has been applied on all the surfaces that are the interfaces between copper and vacuum and it has been also applied on one of the two surfaces created by the symmetry reduction. Electric wall boundary condition (also called perfect electric conductor, PEC) means that the electric field tangential component on the selected surfaces is zero. In order to get from the analysis the cavity quality factor, "surface shielding properties" (copper electrical conductivity equal to 0.58×10^{8} [S m^{-1}]) has been applied on the vacuum/cavity interface surfaces. The entrance and exit iris surfaces as well as the remaining surface created by the symmetry reduction have been set as "perfect magnetic conductor" (PMC also called magnetic wall). A prefect magnetic conductor boundary is a surface in which the tangential component of the vector magnetic field vanishes. PMC is the Ansys default boundary condition for the high frequency simulations.

The "modal analysis" has been performed using the Block Lanczos method to extract natural frequency and E and H distribution. The analysis frequency range has been set from 2.7 to 3.1 GHz. Fig. 3 and Fig. 4 show respectively the E and H field result at 2.998 GHz.

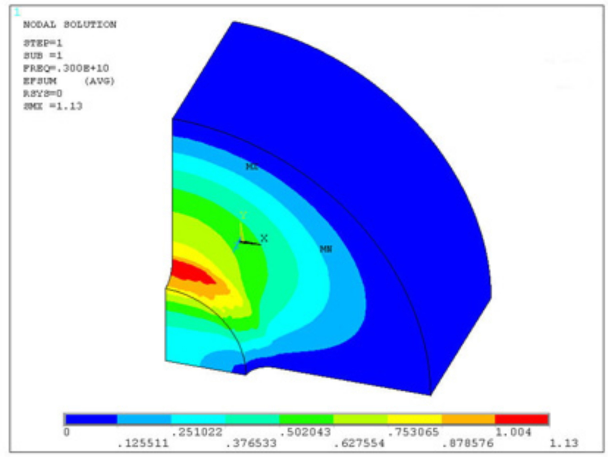

Figure 3: E filed (magnitude) in the vacuum volume

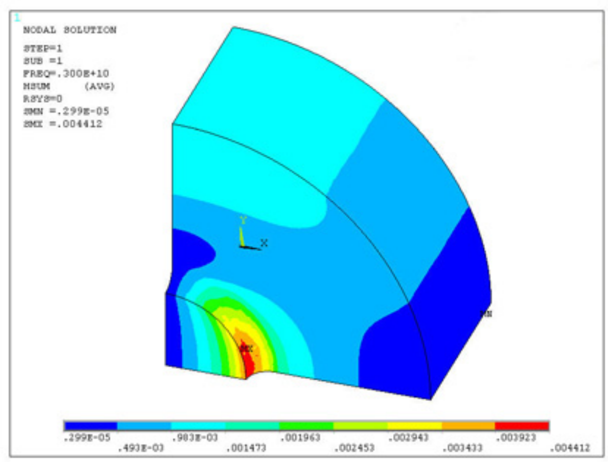

Figure 4: H filed (magnitude) in the vacuum volume

THERMAL ANALYSIS

The next step has been the evaluation of the thermal field in the cavity structure which is made of copper. We have considered only the steady-state condition, that is, the thermal power dissipated on the vacuum/cavity surface is balanced by cooling pipes positioned on the deflector external surface. The Ansys command "ldread" links the high frequency analysis to the thermal simulation. In this way the surface losses calculated in the electromagnetic analysis are applied as heat flux in the thermal simulation. Before applying the thermal load, the heat flux calculated by Ansys has to be scaled with the total dissipated power that is a previously known value. Copper thermal proprieties have been applied to the material and the volume has been meshed with solid87 elements, and the HF119 elements have been turned off. On the contact surface between copper and cooling pipe a convection thermal condition has been applied. For the evaluation of the convection effect, the value of the film coefficient and the fluid bulk temperature value have to be set up. The film coefficient *h* is given by:

$$h = \frac{k}{D} Nu = \frac{k}{D} 0.023 \mathrm{Re}^{0.8} \mathrm{Pr}^{0.4} \qquad (2)$$

where *k* is the thermal conductivity of the water, *D* the diameter of the pipe, *Nu* the Nusselt's number, *Re* the Reynold's number and *Pr* is the Prandtl's number. Fig. 5 shows the copper temperature distribution with 302 K water bulk temperature, and with 120 W of total dissipated power on the single basic cell.

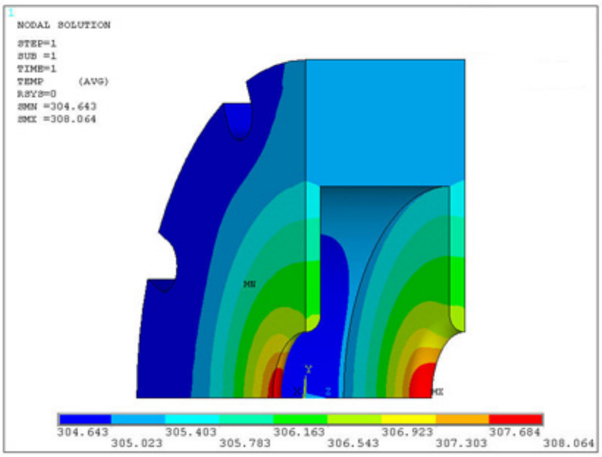

Figure 5: Temperature [K] distribution on the cavity

STRUCTURAL ANALYSIS

The next step has been the evaluation of the structural deformation due to the copper thermal expansion. The same mesh has been used to perform the structural analysis, the elements have only been converted into solid92. With the Ansys command "ldread" the temperature has been passed to the structural environment. On all areas created by symmetry reduction the structural symmetry boundary condition has been applied. Fig. 6 shows the magnitude of the deformation.

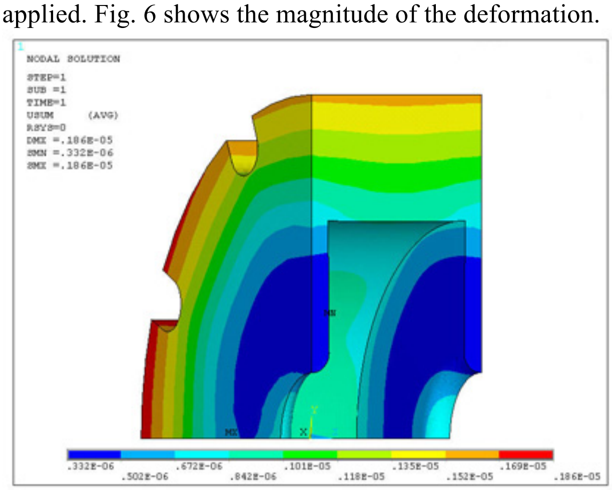

Figure 6: Structural deformation [m] of the cavity

The main effect of the deformation is the cavity diameter increase of about 8 μm. Also a small change of the cavity shape from circular to elliptical is visible. This effect is due to the different temperature distribution on the copper inner surface.

In order to evaluate the effect of this deformation on the cavity natural frequency a electromagnetic analysis on the deformed geometry (by morphing) has been carried out. The natural frequency of the deformed geometry has been decreased to about 400 kHz.

CONCLUSION

A multiphysics analysis performed by Ansys on the FERMI@Elettra RF deflector has been presented. In this paper results of electromagnetic, thermal, and structural coupled analysis have been reported and discussed. Thanks to the start of the commissioning phase, in the coming months there will be an opportunity to compare numerical results with electromagnetic and thermal measurements. The analysis method presented could also be used to simulate other existing and running (at Elettra laboratory) RF structures in order to optimize their thermal stabilization.

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