Multiphysics Design of ESS-Bilbao Linac Accelerating Cavities Using COMSOL

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Abstract: A proton linac (linear accelerator) drives particles using the electric field of a high power RF standing wave in a resonant cavity. The design of these cavities involve several aspects of multiphysics simulation that have been accomplished using COMSOL. The first step consists on the geometric optimization of the cavities in order to have the correct frequency while maximizing some figures of merit. This task involves extensive use of the RF module eigenvalue solver. Detailed 3D simulations follow, to get an accurate description of frequency and fields. From these fields the power loss in the cavity walls is computed and linked to the heat transfer and mechanical module. Some aspects of different accelerating structures (Buncher and spoke cavities) of ESS-Bilbao linac will be discussed.

Keywords: Optimization, resonant cavity, accelerator, power loss

1. Introduction

ESS-Bilbao [1,2] is a research center devoted to science and technology of particle accelerators. Its main facility is a proton linear accelerator (linac) currently in the final design stage. A proton linac drives particles using the electric field of a high power RF standing wave of a certain frequency in a resonant cavity. The design of these cavities involve several aspects of multiphysics simulation, that have been accomplished using COMSOL.

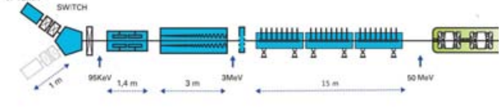

Figure 1. Schematics of ESS-Bilbao linac.

The design of a cavity starts with the optimization of its geometrical shape, optimized in order to have the right resonant frequency. This task involves extensive use of the RF module eigenvalue solver, in connection with Matlab or Java scripts for the optimization algorithms and the cavities figures of merit calculation. This is done in 2D axysimmetric models when possible.

When the final geometric design is chosen, detailed 3D eigenvalue simulations are run in order to get an accurate description of resonant frequency and electromagnetic fields in the vacuum and in the walls of the cavity.

From these fields the power loss in the cavity walls (mainly made of copper, but some of superconducting niobium) is computed and linked to the heat transfer module in order to compute temperature distribution in the cavity solid body. These simulations help to design the mechanical aspects of the cavity.

The changes in temperature modify the cavity geometry, computed using thermal expansion modules, so the cavity geometry is modified and a new eigenfrequency simulation is needed. This loop process is run several times until a convergence is achieved.

Several cavities design will be presented in this work:

- Buncher cavity: Cavity that operates in the Medium Energy Beam Transport section of the accelerator, at 3 MeV. This cavity is made in copper. The work presented correspond to the geometric optimization of the cavity and the thermo-mechanical calculations to determine the adequate cooling strategy.
- Spoke cavity: This cavity type is a superconducting cavity made in Niobium and designed to operate at 4K. It will accelerate protons starting with an energy of 50 MeV. The design of these kind of cavities faces additional challenges, as the design is very sensitive to accurate computation of surface electric and magnetic fields. A benchmark of COMSOL including comparison between simple models with known analytical solution and the simulations are included.

2. Accelerating cavities

A charged particle in an accelerator is driven by the use of RF waves. Acceleration of charged particles using constant voltages applied between electrodes is limited in practice by technological aspects (mainly electrical breakdown) to voltages around 100 kV. In order to reach the high kinetic energies used in proton and ion accelerators (50 MeV in our case) another technique must be used: RF acceleration. The accelerating voltage is in this case taken from the electric field of a sinusoidal RF wave. There are two ways of doing this. In the case of a traveling wave accelerator, the wave propagates along the accelerator and the particles movement must be synchronized with the wave velocity so the particle is always in the top part of the wave feeling maximum electric field (this, of course, needs some means to reduce the wave group velocity below c, the speed of light). Another option, which is the used in most proton and ion accelerators, is to use a standing wave that resonates inside a cavity. As the RF power is supplied by an amplifier of defined frequency, the first task in the design of the cavity is to tune its resonant frequency to the correct value. This is done by optimizing the cavity geometry as will be described in this paper. Frequencies of the order of microwaves are needed in order to have cavities of reasonable transversal dimensions. Again, the path of the particle through the cavity must be synchronized with the wave in order to achieve the maximum possible acceleration.

The design of cavities involves multiphysics simulations in all stages: RF eigenvalue studies to determine the optimum geometry and the electromagnetic characteristics, thermal heating of the metallic walls by the field induced currents, thermo-mechanical calculation to design cooling, etc.

Particles do not travel along a linac in a continuous train, but rather are packed in groups called bunches that are really the ones that are synchronized with the wave. In some stages of the accelerating and focusing process, the bunch of particles can spread out longitudinally, and to re-bunch them close packed again a special accelerating structure known as a re-bunching cavity is employed. This cavity will be described in section 3.

Cavities like the described above have normal conducting walls and operate at room temperature. As power is lost in the copper cavity walls due to induced currents, it can be more efficient to use superconducting cavities made of niobium and operating at temperatures below 4.2 K. The design of these cavities has additional difficulties, because a slight local increase of surface temperature, current or magnetic field can suppress the superconducting state in the entire cavity in a catastrophic effect known as “quenching”. The design of such a cavity is described in section 4.

3. Optimization of a rebunching cavity

After the bunch of protons have been accelerated up to 3 MeV in the RFQ accelerating structure, the longitudinal and transversal distribution of particles is slightly broadened. In order to prepare the bunch to enter the next accelerating structure (the DTL) the bunch must be compacted again. The longitudinal compacting is done using a special kind of accelerating cavities known as “rebunching” cavities. The general appearance of these cavities is shown in figure 2.

Figure 2. Simplified model of a rebunching cavity.

The distribution of electric and magnetic fields in a 2D axysimmetric model are shown in figure 3 for a typical cavity in the accelerating mode (TM, 352.2 MHz). The gap region corresponds to the highest electric field as expected, while magnetic field concentrates around the nose tubes, so they become also a high power loss region.

3.1 Geometrical optimization

The aim of the optimization process is to maximize the effective shunt impedance (*ZTT*) of the cavity (see definitions in Table 1 in the Appendix), a figure of merit that is a measure of the kinetic energy gain of the particle related to the power loss in the cavity walls. So for cavities with the same frequency a higher value of the ZTT means that the cavity generates less heat for achieving the same acceleration. This figure depends on the particle initial velocity, which is βc=0.079732 for protons at 3 MeV. A constrain in the maximization process arises from the Kilpatrick limit, which is the theoretical maximum electric field that a copper conductor can withstand before sparkling starts due to electric breakdown (this value is about 18.5 MV/m for fields at 352.2 MHz). The maximum surface field is computed and related to this maximum as the Kilpatrick factor, *K*. Constrains can be set to K<1.4 for conservative approaches. The geometrical parameters of the cavity (half cavity in 2D axysimmetric representation) are shown in figure 4.

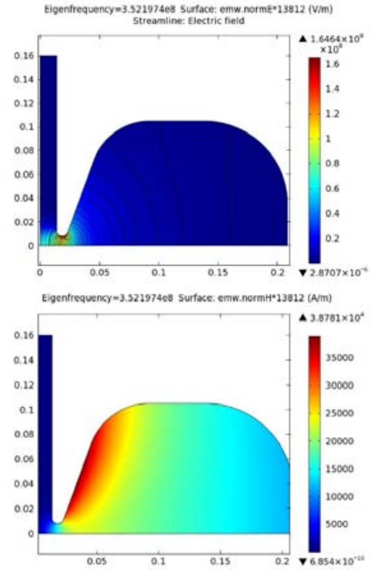

Figure 3. Distribution of electric (up) and magnetic (down) fields in the TM mode of a typical re-bunching cavity.

Optimization is done by different algorithms, but all of them make use of an evaluation function. For a given subset of $n-1$ size of the set of n parameters $X=\{x_i\}_{i\neq j}$, there exists only a value of the constrained parameter x_j that results in a cavity with the right resonant frequency f_0. The finding of the value of x_j for a given set X is a first optimization process common to all methods. This is done by a common one parameter recursive optimization method. In each step, a parameter value equal to the middle point of the interval $y_0=(y_{min}+y_{max})/2$. For the whole set of parameters $\{x_i\}+x_j$, *with* $x_j=y_0$, a COMSOL model is created and solved (inside a Java or Matlab script), and the results analyzed to extract the resonant frequency of the first TM mode. The number of eigenfrequencies obtained is set to 6, because the frequency of the correct mode is not known in advance, and the fundamental mode may not be the TM mode wanted. This step involves the calculation of electric and magnetic energies in the vacuum volume to discriminate real from spurious modes (because $W_e=W_m$ for a real mode), and analyzing $\boldsymbol{E}$ field to identify the mode as TM. If the obtained value is higher (lower) than the target frequency the leftmost (rightmost) half of the interval is chosen for next iteration until the value is chosen with a defined accuracy.

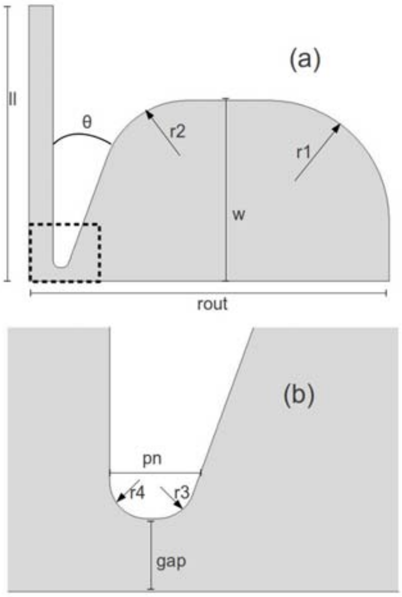

Figure 4. Description of the geometrical parameters of the rebunching cavity (a), with the gap area zoomed (b).

The above described procedure enables us to have an evaluation function $Z(X)$ to compute *ZTT* for a certain geometry $X=\{x_i\}$. To introduce the Kilpatrick constrain, $K<K_0$, different strategies are considered. The most direct approach is to reject any X with K>=K0. As any increase in *ZTT* results in higher K, this leads to discontinuous functions near the optimum value, which is no good for the algorithms. The current approach is to penalize the value of *ZTT* multiplying by a decay factor above *ZTT*. Other approaches are considered, and work on this topic still goes on.

Different algorithms are being used for the final cavity optimization. A first parameter sweep results in an initial model with good enough characteristics. This model is taken as the initial point for optimization using stochastic hill-climbing and genetic algorithms.

Although this work is still ongoing because the final parameters for cavity are not yet frozen, some results are presented here. In figure 5 the evolution of the optimized shunt impedance is shown for a stochastic hill-climbing algorithm, where four geometrical parameters were being modified.

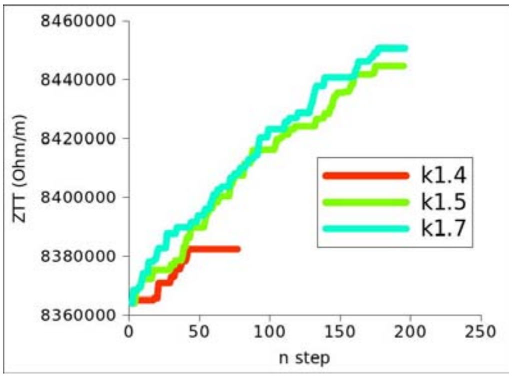

Figure 5. Evolution of optimum result using a stochastic hill-climbing algorithm, for different values of the maximum allowed Kilpatrick factor.

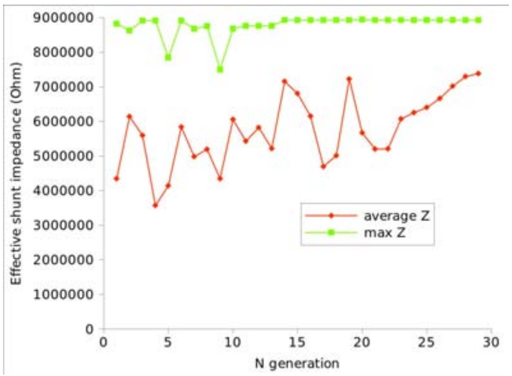

Figure 6. Evolution of the optimization using a genetic algorithm. Average and maximum values of ZTT for all individuals in each generation are shown.

3.2 Thermal calculations

The geometrical optimization described above refers only to the vacuum volume inside the cavity. The outside world must also be investigated. The copper wall of the cavity withstands induced currents that generate heat. If the heat is not removed by an adequate cooling design, the thermal dilatation of the cavity will modify the geometry, changing the electromagnetic characteristics. The most critical area is the nose region, as the gap distance has a very high influence on the frequency and the maximum field.

Based on the work on similar cavities [3-5] a cooling scheme with six radial cylindrical channels is studied (figure 6). As the machining of the cooling channels is complicated, the first designs correspond to simple schemes. The multiphysics problem is then solved. The power loss on the internal walls is taken as a heat flux input for the thermo-mechanical solver. This allows computing the deformation of the cavity, and thus the change in resonant frequency (detuning) that must be corrected by the cooling scheme or compensated by the dynamic tuning device, as described later.

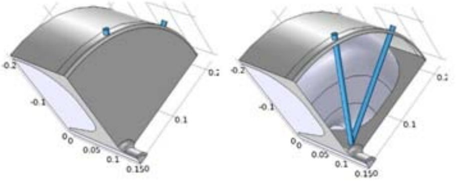

Figure 7. A quarter of a cavity with a simple cooling system to estimate thermal dilatation.

Temperature and displacement maps are shown in figure 7 for different conditions of water cooling temperature (kept constant by the chiller device) and operational duty factors (ratio of actual power to maximum power that the klystron can provided; duty factors of 10% are considered very high for a pulsed linac). The results obtained are summarized in figures 8 and 9.

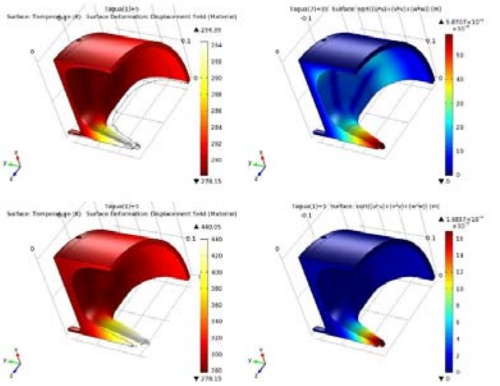

Figure 8. Temperature (left) and displacement (right) field maps for the rebunching cavity operating at 1% (up) and 10% (down) duty cycle, both with the same cooling temperature.

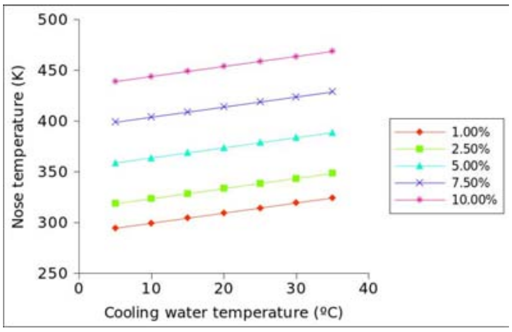

Figure 9. Dependence of the temperature of a point in the nose as a function of water temperature for different operational duty factors.

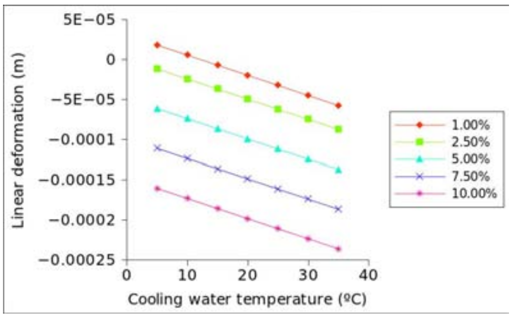

Figure 10. Dependence of the longitudinal displacement of a point in the nose as a function of water temperature for different operational duty factors.

4. Surface fields in a spoke cavity

Spokes cavities are a special type of superconducting resonator that have received an increasing interest for their application in high power proton linacs ([6,7]). ESS-Bilbao plans to fabricate two prototypes of spoke cavity, with the corresponding cryomodule, and test them with beam at 50 MeV.

Electric field distribution in the accelerating mode of a spoke cavity is shown in figure 10.

A critical aspect in the design of superconducting cavities refers to the calculation of surface fields. The total electric losses in the cavity determine the maximum accelerating gradient that the cavity can achieve. If surface fields are not accurately computed, it can be the situation that during operation or testing the surface fields are higher than the design ones. In a normal conducting cavity this results in higher power losses that can be compensated with the cooling system. But in superconducting cavities the increased fields can results in suppression of the superconductor state due to overcoming the critical surface current, magnetic field or temperature. For this reason, special care is taken in computing these fields.

A common benchmark for these fields is the use of volumes with known analytical solution. In this work we show the results of COMSOL with this benchmark [8]. Part of these results have been presented in [9] and are included here for discussion within COMSOL community.

The results correspond to the modes of a sector of conducting sphere. About 30 eigenvalues are obtained, and for each of it the surface magnetic field and the resonant frequency are extracted and compared with the analytical ones. Different mesh sizes and types are computed. Results are shown in figure 11. It is concluded the magnitude of resonant frequency is accurately obtained in most cases, but surface field values need careful attention to the mesh sizes. In any case, the results obtained using COMSOL 4.1 are in general better or similar to the obtained with other codes (see [8]).

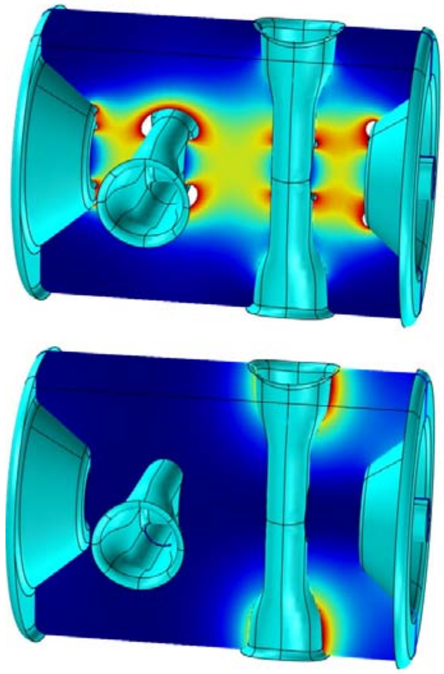

Figure 11. Distribution of the amplitude of electric (up) and magnetic (b) fields in the accelerating (π) mode of a spoke cavity.

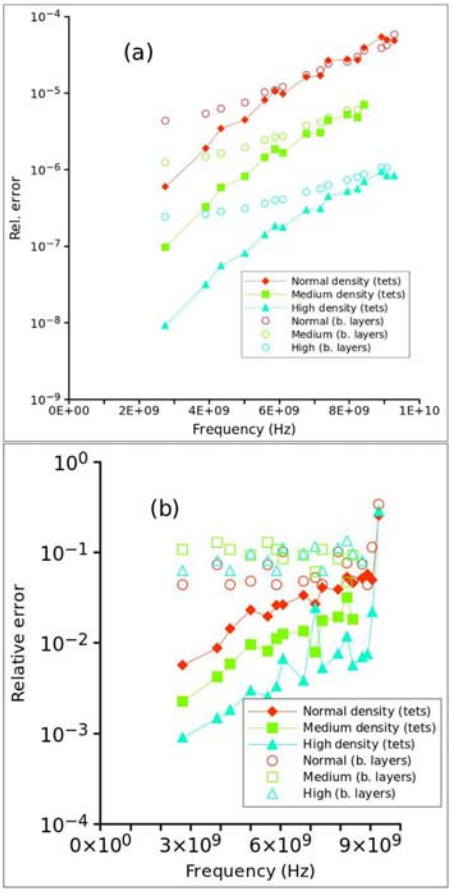

Figure 12. Difference of simulation results from analytical ones for the electromagnetic resonant modes of a sphere. Differences in frequency (a) and surface electric field (b) are compared.

5. Future activities

Concerning the buncher cavity presented here, a prototypes will be built in aluminum before the final fabrication is done. This cavity will enable the comparison of the simulated results with measured ones. This aluminum has already been done for the spoke cavity and the results of the analysis has been presented elsewhere [10], but further work needs to be done. Concerning the most important accelerating structure of the linac (the RFQ and the DTL) design and research activities are ongoing. All this activities are being done using COMSOL multiphysics as main design tool.

6. Conclusions

COMSOL is being used as multiphysics design tool in the activities related to the design and research and development of resonant cavities for ESS-Bilbao linear accelerator.

In this work, the geometrical optimization of a rebunching cavity and preliminary thermomechanical calculations are presented. A benchmark of surface fields, useful for superconducting cavities simulations, is also included.

7. References

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9. Acknowledgements

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10. Appendix

Table 1: Magnitudes used for cavities characterization. See [11] for more details.

Name (symbol)	Definition	2D half cavity
Quality factor (Q)	$\omega W/P$	$\omega W/P$
Angular frequency (ω)	$2\pi f_0$	$2\pi f_0$
Total EM energy stored (W)	$\int (w_e + w_m) dV$	$\int (w_e + w_m) dS$
Power dissipation (P)	$\frac{1}{2} R_s \int H^2 dS$	$\frac{2\pi}{2} R_s \int H^2 dl$
Surface resistance of copper (R_s)	0.0052 Ohm	0.0052 Ohm
Electric field amplitude (E_0)	E_0	E_0
Static voltage (V_s)	$\int_{-L/2}^{L/2} E_{0z}\, dz$	$2 \int_0^L E_{0z}\, dz$
Particle velocity (βc)	βc	βc
Effective electric field (E_0T)	$\frac{1}{L} \int_{-L/2}^{L/2} E_{0z} \cos\left(\frac{\omega z}{\beta c}\right) dz$	$\frac{2}{L} \int_0^L E_{0z} \cos\left(\frac{\omega z}{\beta c}\right) dz$
Transit time factor (T*)	$\frac{1}{V_s} \int_{-L/2}^{L/2} E_{0z} \cos\left(\frac{\omega z}{\beta c}\right) dz$	$\frac{2}{V_s} \int_{-L/2}^{L/2} E_{0z} \cos\left(\frac{\omega z}{\beta c}\right)$
Shunt impedance (Zs)	V_s^2/P	$V_s^2/4P$
Eff. shunt impedance (ZTT)	$Z_s T^2$	$Z_s T^2$

(* If time origin defined as t=0 when particle crosses z=0, center of cavity)