Design of ESS-Bilbao RFQ Linear Accelerator

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Abstract: The design of ESS-Bilbao RFQ (RadioFrequency Quadrupole) linear accelerator cavity using COMSOL Multiphysics is presented. In this paper, the different steps in the design process are described in detail. The work includes geometry definition, electrostatics, electromagnetic and thermomechanical coupled simulations. After several years of development, the design process for this device in ESS-Bilbao has finished successfully and fabrication has been launched.

Keywords: RFQ, electromagnetic, particle accelerator

1. Introduction

The design of an RFQ is a challenging multi-scale problem. ESS-Bilbao [1] RFQ accelerator is a 3.2 m long copper cavity with relevant geometric features in the range of the tens of microns. The cavity design starts with the definition of the vane modulation; the geometry is then built in COMSOL geometry modeler or imported from external CADs. Steps in the design process involve different simulation physics: electrostatics, electromagnetic, heat transfer and thermo-mechanical. These are usually coupled.

An RFQ is a linear accelerator used in proton and other ions accelerators as the first element of acceleration, typically accelerating particles from tens of keV to about 3 MeV. The RFQ fulfills three different tasks at the same time: i) accelerates the beam, ii) keeps it focused transversely, and iii) group particles longitudinally in bunches, optimizing the acceleration performance for the next RF cavities (DTL, superconducting,...). All these characteristics are obtained from the particular distribution of electric and magnetic fields when the cavity is excited with the frequency corresponding to adequate resonant mode. The cavity geometry must be designed to resonate at this particular frequency.

Physically, ESS-Bilbao RFQ is a copper cavity of about 3 meters long, built by attaching together 4 segments of about 800 mm. Each segment is itself formed by 4 elements known as vanes. This allows to achieve the high mechanical requirements needed. A longitudinal cross section of the RFQ can be seen in Fig 1. The different geometric characteristics of the cavity and the operation of the device will be described in this paper following the design process.

All the simulations have been done using COMSOL Multiphysics up to 4.3b version.

1.1 ESS-Bilbao RFQ characteristics

Main RFQ characteristics are described in table 1.

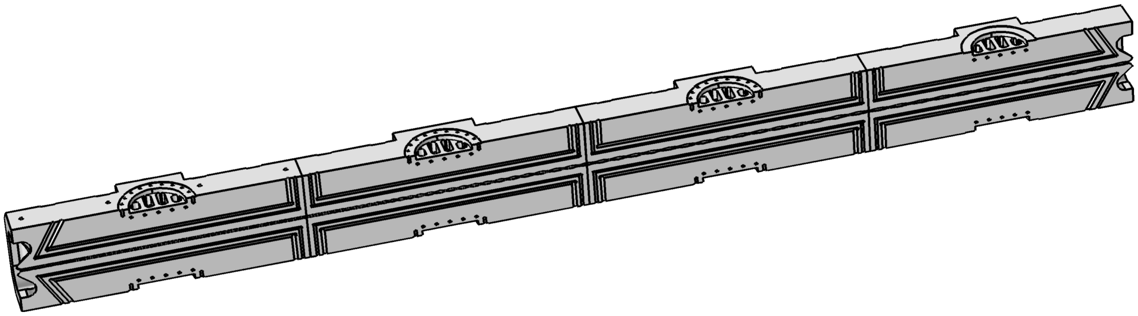

Figure 1: Longitudinal cross section of an assembly of the RFQ. The internal channels for cooling and the vacuum ports can be seen. The proton beam travels along this structure through its central area, where it is accelerated and focused.

Table 1: Main ESS-Bilbao RFQ characteristics

Characteristic	Value
Type	4-vane, pulsed
Particle	Protons
RF frequency	352.2 MHz
Intervane voltage	85 kV
Beam energies	45 keV → 3.0 MeV
Total length	3.12 m (3.66 λ)
Kilpatrick factor	1.85
Number of segments	4 (≈ 800 mm)
Current and emittance	60 mA / 0.25 π mm mrad)

For a complete description of the design and the RFQ characteristics please refer to the Technical Design Report [2].

2. Cavity design

The design of the cavity (determining its geometric characteristics) involve different steps that needs specific simulation means. These design processes are described in this section.

2.1 Transverse cross section design

Cavity cross section in an RFQ has a very particular shape. In the operational resonant mode the electric field is concentrated in the intervane region, and corresponds to a transverse quadrupolar electric field. Magnetic field is distributed in the external circular lobe area, and is perpendicular to the cross section (Fig. 2). A detail of the electric field map in the central region where the beam travels is shown in Fig 3.

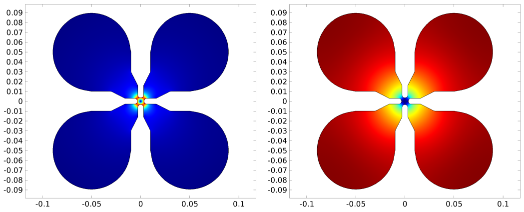

Figure 2: Distribution of electric (left) and magnetic (right) fields for the right mode frequency.

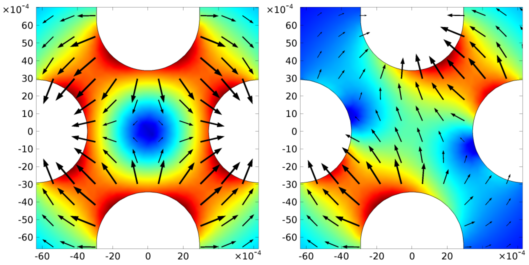

Figure 3: Surface and arrow maps for the electric field for the quadrupolar operational mode (left) and for one of the dipolar modes (right) that are very close in frequency.

The geometry of the cross section is designed taking into account certain constrains: vane tip shape is determined by beam dynamics design; resonant frequency by RF operation and external shape is conditioned by mechanical restrictions (overall dimensions, cooling channels position).

The design is done using COMSOL 2D electromagnetic eigenfrequency parametric simulations. For each set of geometric parameters, one is left free; this one is computed by an optimization script to make the cavity match the fixed resonant frequency. Each set of parameters results then in a cavity with the right frequency. To choose the optimum set of parameters, each model is evaluated by computing cavity figures of merit, particularly power loss in the copper walls. The design with the lowest power losses is chosen.

The quadrupolar field (Fig. 3, left) is the operational mode. This field focuses the beam in the X and Y directions, alternatively as the polarity of the RF excitation varies. The design process tries to get the undesired dipolar modes (Fig. 3, right) separated several *MHz* from the quadrupolar mode.

2.2 3D design of the vane region

With the process described in the previous section an RFQ would be just a beam transport and focusing device. The acceleration and bunching capabilities of an RFQ, which are what makes it an outstanding device for particle accelerators, is derived from the modulation of the vanes.

In Fig. 4 a detail of the longitudinal vane modulation is shown. Modulation causes that the electric field on the central axis has a longitudinal component, that is the responsible of the acceleration. Each semi-period in the sine-wave-like modulation is called a cell. This pattern must be spatially synchronized with the RF electric field, so the traveling particle beam sees always a positive accelerating component regardless of the polarity of the RF wave. The wavelength of the modulation increases cell to cell, so the accelerated particle gets the maximum kick from the field in each cell. Its length is then $\beta\lambda/2$, where β is the particle speed in units of speed of light and λ is the wavelength corresponding to the 352.2 MHz.

Design of the vane modulation makes use of an electrostatic analogy, where the electric field distribution in the RFQ quadrupolar mode is represented using electrostatic voltages, constant for the *X* and *Y* vanes. Due to the particular semi-circular shape of the vane tips, the field distribution is exactly the same than for the RF mode. Modulation parameters are designed using specific beam dynamics codes that takes advantage of this analogy.

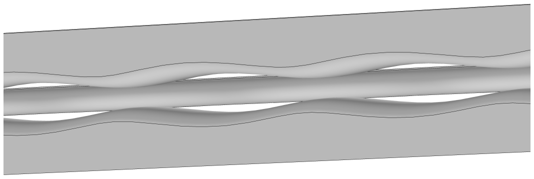

Figure 4: Detail of the longitudinal vane modulation.

Longitudinal component of the electric field on the axis (*Ez(z)*) is shown in Fig 5. This curve is the same computed by electrostatics of electromagnetic simulations, but for an scale factor; in the later case this magnitude represents the accelerating field amplitude.

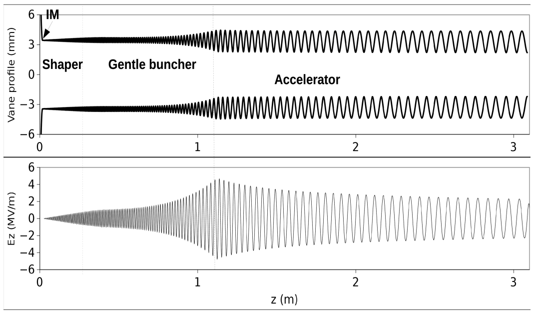

Figure 5: Vane profile (up) and corresponding accelerating field, Ez(z) (down), for the RFQ. Field computed using a electrostatics simulation.

Concerning COMSOL simulations, the main difficulties come from the geometric modeling of the vanes and the calculation of surface fields. The size of the meshes are about 500 ktets to 1.5 Mtets.

The geometry of the vanes must be represented with accuracy around tens of microns to correctly reproduce the longitudinal profile. The construction of the solids of the vane tips was initially done with an external CAD package and then imported in COMSOL via step files. The accuracy of the solids built this way was not enough for our purposes. For cell-by-cell simulations (short lengths) the best solution was to build the geometries directly in COMSOL geometric modeler, using parametric surfaces. For example, for the vane *X* between coordinates z_0 and z_1, the vane profile is defined as in Eq 1,

$$\begin{cases} x = V_x[z(u)] + \rho(1-\sin(v)) \\ y = \rho\sin(v) \\ z = z_0 + u(z_1 - z_0) \end{cases} \qquad (1)$$

where the parameter *u* goes from 0 to 1, *v* goes from -π/2 to π/2; $V_x(z)$ is the profile of the *X* vane tip along *z* axis, imported using an interpolation function, and ρ is the radius of the vane tip. With the whole length of the RFQ the modulation built this way showed some discrepancies with the theoretical profile. We think that the one to blame is the interpolation algorithm in COMSOL. For fabrication specifications the solids were built using a home made code that uses OpenCascade.

Electrostatic simulations are also used for another issue concerning vane modulation design. Particle accelerators operate in vacuum with very high power radiofrequency electromagnetic fields. It is custom to refer the maximum allowed electric field to the so-called Kilpatrick limit. Surface fields above this value increase the chances for sparks due to surface field emission, that will ruin the operation of the device. The theoretical field limit for a copper surface at 352.2 MHz is about E_s=18.4 MV/m. In our design the maximum value is chosen to be 1.85 Kilpatrick, about 34.1 MV/m. This value, which is normal for similar RFQs, is much higher than the theoretical limit due to the better vacuum and surface finishing conditions achievable nowadays. The profile of the surface field is an optimization target, in our design we aim to get the highest acceleration possible without exceeding our design limit. The surface field profile for the final model is shown in Fig. 6. The profile is not uniform, reflecting the different tasks for the modulation at different *z* (bunching, accelerating,...) connected to the quality of the proton beam optics.

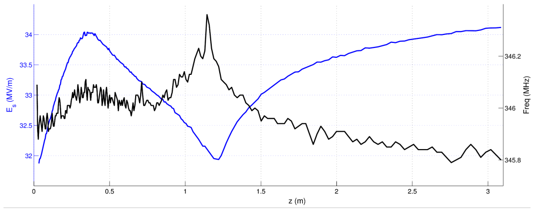

Figure 6: Longitudinal profile of the surface electric field (blue, left) and the local frequency (black, right) for the final design of the RFQ.

2.3 Complete 3D design

The 3D internal shape of the RFQ is obtained extruding the 2D cross section along the total length, and then inserting the vane modulation. The target of the 3D electromagnetic design is to obtain a resonant cavity with a quadrupolar resonant mode at the operational frequency, trying to have an electric field along the axis as similar as possible to the one designed by electrostatic computation in the vane region. This task is rather challenging.

The RFQ cross section (like in Fig. 2) can be assumed to be an LC resonator with the capacitance being the intervane region and the inductance the external lobes where magnetic field flows. Frequency is then simply $\omega=1/\sqrt{(LC)}$. The outer lobes have the same shape for all the length, but the intervane distance is a function of *z* due to the vane modulation. This results in a non-uniform local frequency variation, as is shown in Fig. 6. The resonator then behaves as a composite of multiple frequencies. This can be studied representing the resonant cavity with a transmission line model, where instead of a single frequency resonator a whole spectrum of frequencies is obtained.

One important step in the transition from the electrostatic to electromagnetic models is related to scale. The electrostatics represents the ideal design fields, with the vane tips forced to have a uniform voltage of $+V_0/2$ or $-V_0/2$. The fields in the electromagnetic eigenfrequency solution will not have the right magnitude, as there is not power input reference for the fields. In order to compare the electromagnetic solution to the electrostatics ones (to obtain real voltages, surface fields, power deposition, etc) an scaling process needs to be done. We have chosen to compare the volume averaged electric field in the axis region and to obtain a scale factor from the comparison: $f=|E_s|/|E_{em}|$. This factor will multiply all fields (*E* and *H*) in the electromagnetic solution.

A consequence of the non-uniform frequency described above is that when the cavity is excited with a single frequency (for example the operational frequency, equal to the fundamental frequency of the spectrum), due to the fact of having $L\neq L(z)$ and $C=C(z)$, is that vane voltage is no longer uniform along *z*. This is the main difference between the electrostatic ideal model and the electromagnetic realistic one.

In order to validate the RF models, voltage needs to be extracted and compared to the ideal one. This is done in COMSOL using a script to compute, for each *z*, the total electric energy from the ES and EM solutions:

$$W_{es} = \int_\Omega \frac{1}{2}\epsilon_0 \, |E_s|^2 \, d\Omega; \quad W_{em} = \int_\Omega \frac{1}{2}\epsilon_0 \, |f \cdot E_m|^2 \, d\Omega \quad (2)$$

and voltage profile is obtained from the comparison of the capacitances:

$$C(z) = \frac{2 \cdot W_{es}(z)}{V_0^2}; \quad V_{em}(z) = \sqrt{\frac{2 \cdot W_{em}(z)}{C(z)}} \qquad (3)$$

Another difference between the ideal electrostatic model and the electromagnetic is due to the fact that the cavity is not infinite, but starts and ends at certain *z* coordinates. The compensation of the disturbances caused by the low and high energy ends to the voltage profile is done by designing them with a particular shape, as shown in Fig. 7. The local frequency of the input section is controlled by the shape of the circular part (inductive contribution) and by the distance to the cover (capacitive contribution).

The global perturbation effect on the voltage due to the modulation, the input and output sections and other sources is compensated in the RFQ with the aid of plunger tuners: cylinders that penetrate the vacuum and modify the volume, changing the resonant frequency and the voltage profiles. Even before the application of the tuners, the difference (Fig. 8) between the ES and EM accelerating fields is well below 1% for all the RFQ length.

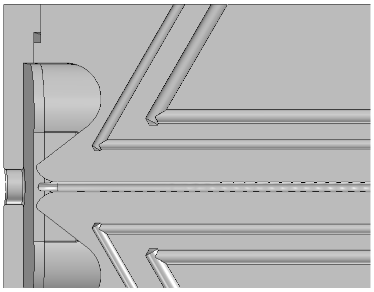

Figure 7: Longitudinal cross section of RFQ, showing the input matching section and the input cover.

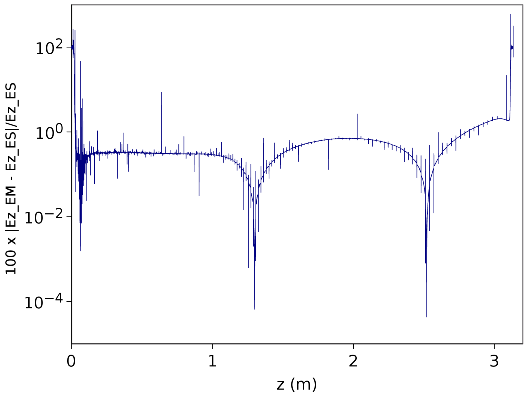

Figure 8: Relative difference between the accelerating electric field E_z in the ideal electrostatic case and in the real scaled electromagnetic case. Plungers tuners, which will further reduce the difference, are not used here.

3. Power loss and thermo-mechanical design

The electromagnetic fields discussed in the previous sections results in power losses in the copper walls. The losses produce surface currents that heats up the metal, so adequate cooling strategies must be considered. Power losses are computed via Poynting theorem as

$$P[W/m^2] = \frac{1}{2}R_s H^2; \;\; R_s = \frac{1}{\sigma \delta_s} \qquad (4)$$

Heat transfer module is used for thermal calculations. The power losses can be incorporated to the model as coupled to the eigenfrequency solution or by importing the data in an interpolated function. This value must be multiplied by the adequate duty cycle factor in the pulsed operation of the RFQ (value between 1% and 10%).

In Fig. 9 (left), the power loss is shown for a quarter of the first segment of the RFQ. The power input is mainly concentrated on the input matching section. Using the heat transfer-conjugate gradient module, taking the power loss as heat source input and cooling water effect with a heat transfer coefficient, the temperature distribution is computed for the segment.

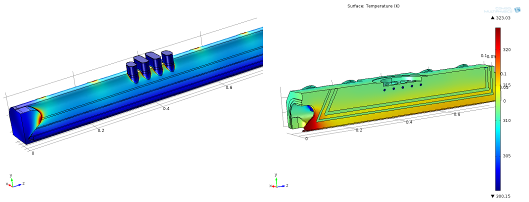

Figure 9: Power loss distribution in the copper surface (left) and temperature distribution in the copper (right) for a quarter of the first segment of the RFQ under operational conditions.

3.1 Deformation and coupled simulations

The temperature distribution in the copper will produce thermal stresses and deformation, that despite being small in magnitude, are enough to modify the internal volume. Particularly delicate is the modulation region. This change will modify the resonant frequency of the cavity, resulting in a mechanical detuning with a reduction of input power and accelerating performance.

To study and control this effect, coupled heat transfer, mechanical and deformed mesh simulations are performed. The deformation of the copper-vacuum surface is transformed into a volumetric mesh deformation using the moving mesh physics. Eigenfrequency simulations are then performed to compute the new resonant frequency. A plot of this dependence is shown in Fig. 10 (steady state simulations).

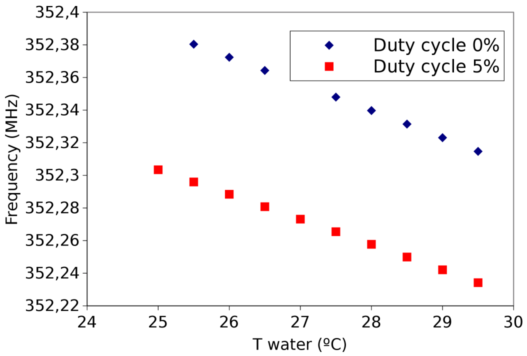

Figure 10: Resonant frequency change of the RFQ cavity depending on the cooling water temperature, for two different duty cycles.

3.2 Dynamic thermo-mechanical simulations

Due to the complex behavior described above, the operation of the RFQ needs a continuous automatic control to keep frequency constant and performance stable. In our design the dynamic control of the frequency is performed by changing the temperature of the cooling water.

In order to develop control models for the operation, time transient simulations of the electromagnetic-thermomechanical-deformation-electromagnetic loop have been done. These simulations are very time consuming. An example of the obtained results is shown in Fig. 11, where power up and power down step transients have been studied.

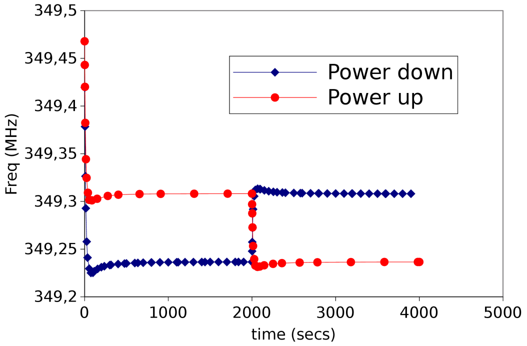

Figure 11: Cavity frequency change for power up and power down steps, computed with time dependent coupled simulations.

4. Conclusions

COMSOL Multiphysics has been used for the challenging task of designing an RFQ linear accelerator. Electrostatic, electromagnetic and thermo-mechanical simulations, usually coupled and scripted have been the main tools for this.

For the correct representation of the geometric fine details, parametric surfaces and specific home-made tools have been used. Modes resulted to have very large meshes due to the small features and large dimensions of the RFQ.

The design of the device has finished and the fabrication procuerement has started.

9. References

1. ESS-Bilbao http://www.essbilbao.org
2. I. Bustinduy and J.L. Muñoz (Editors). Technical Design Report: ESS-Bilbao RFQ, June 2015. ESS-Bilbao Consortium Report Series, ESSB-Rep-2015-010. ISBN-13:978-84-616-5445-1

10. Acknowledgements

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