3 GHz SINGLE CELL CAVITY OPTIMIZATION DESIGN

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Abstract

In order to develop a high gradient S-band electron accelerating structure, an optimized travelling wave (TW) single-cell cavity operating at the frequency of 3 GHz with $2\pi/3$ phase advance, is proposed. Starting from the well-known accelerating cells design developed by the Laboratoire de l'Accélérateur Linéaire (LAL) and the Stanford Linear Accelerator Centre (SLAC), for linear accelerators; it is possible to improve the main RF parameters, such as quality factor, shunt impedance, enhancement factor and group velocity, by choosing a suitable shape of the inner surface [1]. Even though surface electric field is being considered as the only main quantity limiting the accelerating gradient; the importance of power flow and the modified Poynting vector [2], has been highlighted from high-gradient experimental data [3]. In this context, the new field quantity (S_c) is derived from a model describing the RF breakdown trigger phenomenon wherein field emission currents from potential breakdown sites produce local pulsed heating. In particular, the modified Poynting vector takes into account both active and reactive power flow travelling along the structure. The main results presented in this paper have been carried out with the 3D electromagnetic simulation codes: High Frequency Structural Simulator solver (HFSS) and CST MICROWAVE STUDIO (CST MWS).

INTRODUCTION

ThomX is a Compton backscattering compact light source project, aiming to produce an intense flux of monochromatic X rays (40 – 90 keV) resulting from collisions between laser pulses and relativistic electron bunches. The machine consists of a 50 – 70 MeV Linac injector and a storage ring. A demonstrator was recently funded and is going to be built in the Orsay University campus. The Linac injector is composed of a RF gun and one accelerating section able to boost the energy of particles. For the first stage of the machine commissioning, a "LIL"-type accelerating section is foreseen to be lent by the SOLEIL Laboratory, as a partner of the project. This section was developed by LAL-Orsay for the pre-injector of the Large Electron Positron Collider (LEP) at CERN. In order to reach a final energy of 50 MeV, the energy gain in the section must be 45 MeV. However, the accelerator should reach higher energies in order to produce X-rays beyond 50 keV [4]. Since the maximum targeted X-ray energy is 90 keV, the Linac design should allow beam energy of 70 MeV. A LAL-PMB collaboration on high gradient S-band structure research has been established in order to advance together in this field.

The ThomX high gradient structure is a TW quasi-constant gradient section and will operate at 2998.55 MHz (30 °C in vacuum) in the $2\pi/3$ mode. It will be fabricated by PMB in order to increase the ThomX Linac energy up to 70 MeV, with an available input power of about 20 MW. The final structure will be made of 94 accelerating cells and 2 coupling cells.

RF DESIGN OPTIMIZATION

The accelerating gradient is limited by RF breakdown in normal conducting TW structures and it has been observed to depend on many parameters including surface electric field, pulse length, power flow and group velocity [5].

For a long time, the surface electric field was considered to be the main quantity which limits accelerating gradient because of its direct role in field emission while the magnetic field was considered to be unimportant. However, as more experimental data had been taken into account, it was clear that the maximum surface electric field could not serve as an ultimate constraint in the RF design, because of its large variation in different structures. New ideas about the ratio from the input power flow to the minimum iris circumference P/C as a better constraint to be used in RF design, appeared since 2006. Although the P/C parameter fits a large fraction of experimental data, deviations were observed from geometries scaled to different frequencies.
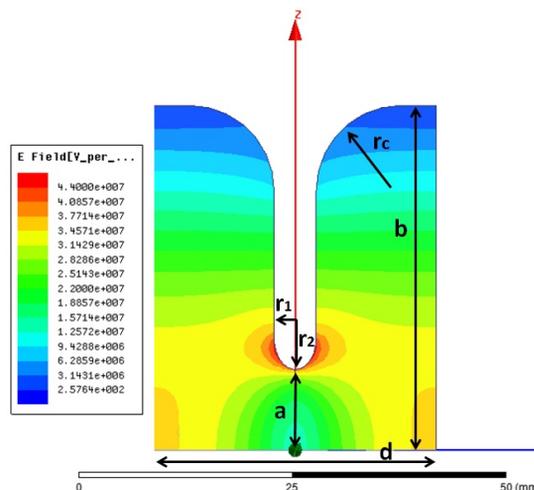
Figure 1: 2D section and electric field distribution of the half single cell.

A new model, is still based on the local complex power flow S (Poynting vector), but it also considers both a real and imaginary part of it, representing a combination of local electric and magnetic fields which sets a limit to achievable gradient.

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The 2D profile of the single cell with its main geometric dimensions is given in Fig. 1. The cell period d is set by the mode phase advance, $2\pi/3$. The iris is characterized by an elliptical shape with minor and major axes $2r_1$ and $2r_2$, respectively. The cell radius b is a derived number given by setting the cell resonant frequency, f_{RF}.

In order to evaluate the RF efficiency of a single periodic cell, some approximated analytical correlations linking the geometric dimensions of the cell to the main RF figures of merit, can be considered. In particular, considering the main RF parameters, such as Q-factor, shunt impedance per unit length r, ratio between the peak surface electric field E_{speak} and the average accelerating field $< E_a >$, group velocity v_g; the global properties of the cell can be predicted as a function of the inner radius a and the thickness $t = 2r_1$ of the iris, for the suitable ratio of r_2 to r_1 [6].

The 3D electromagnetic codes HFSS and CST MWS allow to simulate periodic structures by only using one period and applying proper boundary conditions. The conditions "master and slave" for HFSS and "periodic" for CST MWS enable to impose a phase shift, 120 degrees between the two outer faces of the single cell. Then, a simulation with the eigenmode solver finds the frequency at which the electromagnetic field satisfies the phase shift desired. Exploiting the symmetry in the field only one quarter of the whole cell was used for simulations and a condition of perfect magnetic boundary, called "perfect H" was applied.
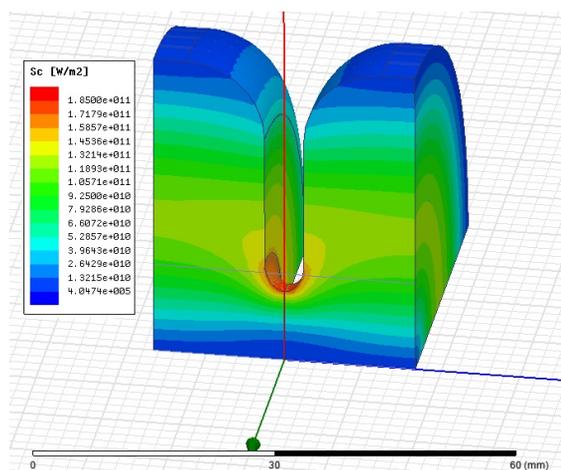
Figure 2: Modified Poynting vector distribution inside one quarter of the regular cell.

In order to mitigate possible breakdowns, a thorough study of the cell shape and corresponding electric field distribution, has been carried out using the electromagnetic codes, already mentioned. The distribution of the modified Poynting vector S_c for one quarter of the full cell, is shown in Fig. 2. Furthermore, from the picture of the electric field distribution (Fig. 1), it is easy to see that the peak value of the surface electric field and the modified Poynting vector, occur around the iris region. Because of this fact, operating at high gradient requires special attention to minimize these quantities. For example, the choice of an elliptical

shape for the iris allows to achieve an electric field at the iris tips, where the surface electric field is locally intense, with intensity lower than the case with iris circular profile.

The final shape should be the best solution in geometrical parameters space using several criteria. First, optimization of r/Q which is a quantity independent of material properties and depends only on the geometry. This quantity provides an estimation of the accelerating field value for a given stored energy per unit length. Second, minimization of the ratio between the peak surface electric field E_{speak} and the average accelerating field on the axis $< E_a >$ which is called electric field enhancement factor [7]. Finally, minimization of the modified Poynting vector S_c as a quantity correlated to the breakdown rate, BDR.

EM SIMULATIONS AND RESULTS

In general, the design of cell geometry is a difficult process because an improvement in one RF parameter usually results in degradation in another one. That is why, the optimum design of the cell is a consequence of the series of trade-off between different cavity parameters aiming to accomplish all operational requirements and the structure machining.

A brief description of the main RF parameters depending on the geometry, is now presented. The cavity radius b, is very sensitive to the frequency of the fundamental mode while marginally affects the electromagnetic and mechanical properties. Hence, the tuning of the cell can be easily performed by varying b, without changing any other independent geometric parameters, such as a, r_1, r_2. By means of the simulations, the relation between the cavity diameter ($2b$) and the iris diameter ($2a$), for a fixed ellipticity ratio r_2/r_1, iris thickness t and the rounded edge of cell r_c, has been calculated in order to maintain a constant frequency ($f_{RF} = 3 \pm 0.004\%$ GHz). This function ($2b$) = f($2a$) has been considered for all of the simulations performed. A round inner edge r_c, for the resonant cell gives higher Q value. Thus, the corresponding quality factor (Q-factor) for different values of the radius r_c, has been calculated while the inner cell radius b was adjusted to maintain a constant frequency ($f = 3 \pm 0.2\%$ GHz). It has to be noticed that the use of a rounded cell edge r_c leads to increased values in the Q-factor more than 10%.
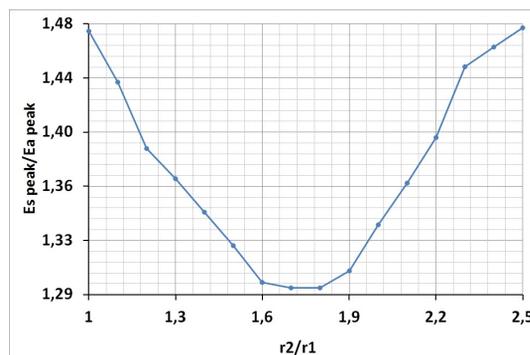
Figure 3: E_{speak} normalized to the maximum accelerating field on axis as a function of the iris ellipticity.

The iris elliptical shape (r_1, r_2), strongly influences the electric field distribution [8]. The choice of the iris shape derives from an optimization process aiming to minimize surface electric field at high accelerating gradient (low field enhancement factor). Such gradient value can be achieved utilizing shape-optimized elliptical iris. Figure 3 shows the ratio E_{speak} and E_{apeak} as a function of the iris ellipticity for fixed values of the iris radius ($a = 10$ mm), iris thickness ($2r_1 = 5$ mm) and rounded edge cell ($r_c = 10$ mm). The plot shows that for a certain iris aperture there is an optimum elliptical profile of the iris itself that minimizes the surface field. The maximum reduction of the surface field is of the order of around 14% with respect to the circular profile.

Figure 4 represents the trend of r/Q and v_g/c for different values of the cell aperture with an iris thickness of 5 mm, r_c of 10 mm and r_2/r_1 of 1.7.
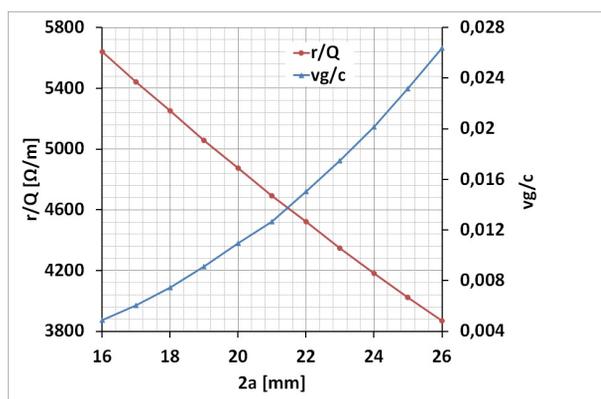
Figure 4: r/Q and v_g/c for different values of the iris diameter.

The iris radius a, is a very important parameter which influences several RF features. Electric field is more focused on axis for smaller iris radius and hence r/Q is higher for smaller a. In addition, field enhancement factor decreases when iris radius is decreasing. Therefore, normal conducting accelerating structures should be built with smaller iris radius to obtain higher r/Q which results in reduction of power dissipation on the wall and lower enhancement factor to increase the accelerating gradient. Nevertheless, large iris aperture $2a$ reduces the filling time of the structure itself leading to shorter required input pulse length. Usually, shorter pulses are preferred as RF breakdown probability increase with pulse length. Therefore, it is easy to see from Fig. 4 the suitable iris radius must be chosen to obtain an high r/Q value for a reasonable value of v_g/c that leads to a filling time lower than the pulse length of the RF power source.

The field emission currents at potential breakdown sites causes pulsed local heating which acts as breakdown trigger in the model used to introduce the modified Poynting vector S_c. The real part of this new quantity $Re\{S_c\}$ describes active power flow along the cell while the imaginary part $Im\{S_c\}$ describes reactive power flow inside the cell. Moreover, the reactive part couples more weakly to the field

emission current than active power flow. Taking into account this fact and the exponential dependence of current emission on electric field, the modified Poynting is presented in the form: $S_c = Re\{S_c\} + Im\{S_c\}/6$. Since S_c is available from numerical RF simulator for every point of the structure, this local quantity can be considered as a new constraint to explain the limited high-gradient structure performance due to vacuum RF breakdown [9]. One of the most interesting aspects of this model is the BDR is proportional to the 15th power of the modified Poynting vector [10].

Figure 5 represents normalized $< E_a >, E_{speak}/ < E_a >$, E_{speak}/E_{apeak} and $S_c/ < E_a >^2$ as a function of the iris aperture $2a$. For an input power of 20 MW the peak value of the modified Poynting vector S_{cmax} is equal to 0.185 MW/mm^2, which corresponds to a maximum value of 44 MV/m for the surface electric field, a maximum accelerating gradient of 35 MV/m and an average accelerating field of 28 MV/m. From this kind of plot, it is evident that lower values of the field enhancement factor and the E_{speak}/E_{apeak} ratio, lead to smaller values of the iris radius a. In the same time, as the BDR is proportional to the 15th power of the modified Poynting vector, smaller values of the iris radius, lead to decreasing the probability of the breakdown in the whole accelerating structures.
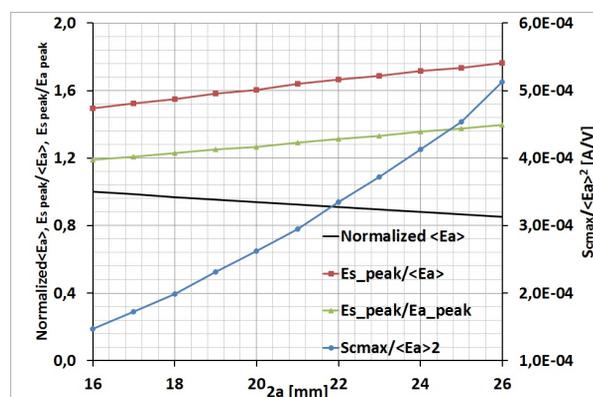
Figure 5: Trends of some RF parameters for different values of the iris diameter.

CONCLUSION

The cell shape has been optimized, with the help of HFSS and CST MWS, in order to get a good compromise between high RF efficiency in terms of acceleration and reduced power dissipation on the inner wall of the cell (high r/Q), with a reasonable value of the filling time τ and the BDR limit based on the modified Poynting vector model. As the optimal set of the single cell geometric dimensions is found, in order to get a good estimation of the thermal and structural effects, thermal analysis and beam dynamics for both RF gun and accelerating sections prototypes are underway.

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