

A RATIONALE TO DESIGN SIDE COUPLED LINAC (SCL): A FASTER AND MORE RELIABLE TOOL

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Abstract

A module of a Side Coupled Linac (SCL) is formed by a cascade of two or more tanks, connected by a Bridge Coupler (BC) with an RF feeder, which realizes a well defined field configuration in all the coupled cavities. Usually the first step of the design consists in the use of 2D and 3D e-m CAD's able to characterize the single cell parameters in terms of its geometrical quantities and to study the behaviour of many coupled cells, respectively. The usual procedure foresees a full characterization only of a tank ended by half cells shorted by p.e.c. flat plates, by using the 3D CAD output (mode frequencies) as an input for specific codes as Disper able to find out the lumped circuit parameters of such a structure. From these values one may only calculate the frequency values for a right termination of the tanks, but no codes are available to check the parameters for a full-cell ended tank.

The new proposed procedure stems from a lumped circuit representation for resonant coupled structures where the equations were studied in any condition of termination. This gives the possibility of having a full characterization either of a half-cell or a full-cell ended structures. Furthermore this procedure foresees an absolutely innovative and more rational design of the BC using its lumped circuit modeling. Finally this rationale to design a module of an SCL allows to study ex ante the full coupled system in order to focus the crucial parameters for its optimum functioning.

INTRODUCTION

The SCL's [1] were conceived in such a way to resonate on the $\pi/2$ mode in order to exhibit a uniform field configuration in the accelerating cells (AC).

In general the design of a module is done by optimizing separately the tanks and the BC. This procedure is iterated till the achievement of satisfactory results.

The design of the tanks is made by means of 2D and 3D specific e-m CAD's, as Superfish and MicrowaveStudio. The 2D CAD's are used in a first step of the designing in order to study the single cell frequency behaviour with respect to its geometrical parameters. The 3D CAD's are a fundamental tool in order to study the mode frequency response of a certain number of coupled cells. A good compromise for 3D analysis of a tank is to isolate a certain number of cells representative of the whole tank (three

AC's plus two CC's or more, if the case) ended by half cells shorted by p.e.c. flat plates. This model can be assumed as the device under test for numerical "measurements".

The usual procedure takes the mode frequency response coming from the e-m CAD and resorts to specific codes, as Disper, in order to get the values of AC and CC frequencies, f_a and f_c , the first and second neighbors coupling constants, k_1 , k_a and k_c . By using these values one may check the goodness of the system, this can be done by checking the value of the band-gap defined as [2]

$$\Delta = f_{\pi/2}^{AC} - f_{\pi/2}^{CC} = \frac{f_a}{\sqrt{1-k_a}} - \frac{f_c}{\sqrt{1-k_c}} \quad (1)$$

be as small as possible; in addition one should design the end cells such to have the resonant frequency, f_e , according to [3]

$$f_e = \frac{f_a \sqrt{1-k_a/2}}{\sqrt{1-k_a}}. \quad (2)$$

However up to now there are no codes available able to give a reliable value of the f_e for a full-cell termination structure.

For the other tanks, while the longitudinal dimensions have to be scaled in proportion to the particle velocity, in order to keep the transit time factor constant, it is appropriate to keep the transverse dimensions constant. The tuning is obtained changing the nose geometry and the septum dimensions.

The BC is designed as a three cell structure having a central cavity working as an AC and two lateral cavities working as CC's. The rule of thumb is to give their frequencies equal to the corresponding ones of the tanks. Even if in the literature there is no clear statements on this subject, to our knowledge the optimization on the whole system is done "ex-post" by means of a tuning procedure.

The possibility of studying "ex ante" this kind of devices with a petty time consuming, permits to focus the crucial parameters for the well functioning of the whole system by using the mode frequencies coming from the e-m 3D CAD as "measurements" and solve these systems in terms of the lumped circuit parameters.

TANK DESIGN

A tank of an SCL structure is formed by a certain number of AC cavities and a certain number of CC off-axis cavities. It is possible to represent the total structure as a biperiodic chain of resonant circuits [2, 3, 4, 5, 6].

The tank design consists in three steps.

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The first step is to draw a five half-cell structure in a 3D e-m CAD and to get its system mode frequencies. For a five cell structure it is possible to show that the five order lumped circuit equations can be factorized in two equations one of the second order and another one of third order. This factorization permits to build a home-made code in Mathematica which uses the system mode frequencies and gives the coupling constant coefficients and the AC and CC frequency values. Therefore one may check the band-gap value and to calculate the theoretical value of the end cell frequency by using equations (1) and (2).

Afterwards, in the second step, one designs the end cells. In a way similar to the one of the first step, a new five cell structure full-cell ended is realized, analyzed by CAD and its parameters, included the frequency of the end cells, are given by a home-made code in Mathematica the philosophy of which is similar to the previous one.

As a final step, one draws in the CAD a 9 full cell structure in order to study the lowering in the frequency which is a unavoidable effect when the number of cells increases.

By means of a code in Mathematica which uses as an input the 9 system mode frequencies, all the frequency and coupling parameters are obtained resorting to a variational method.

Thanks to our tools we can also foresee the behaviour of a tank in presence of some errors in its nominal parameters. Indeed we studied the field behaviour of the system for different condition of the detuning of the end cells and for different values of band-gap. From these analysis we realized that in the design of our tanks the iterative procedure can be stopped when $\Delta < 1MHz$ and $f_e^{designed} - f_e^{nominal} \leq 1MHz$.

THE BRIDGE COUPLER

The BC has a body completely different with respect to the tanks: it is formed by three coupled cells on axis and their dimensions are larger than the ones of the tanks in order to make easy the flow of the e-m power.

Let us consider a half cell structure composed by a central AC and two lateral half CC's. In the lossless case, the dispersion relation is given by the following equation:

$$\left\| \begin{array}{ccc} \frac{\alpha_c}{2} & \frac{k_1}{2} & \frac{k_c}{2} \\ \frac{k_1}{2} & \alpha_a + k_a & \frac{k_1}{2} \\ \frac{k_c}{2} & \frac{k_1}{2} & \frac{\alpha_c}{2} \end{array} \right\| = 0 \quad (3)$$

where $\alpha_{a,c} \equiv \left[1 - \left(\frac{f_{a,c}}{F} \right)^2 \right]$ with $f_{a,c}$ stands for the resonant frequency of the AC and CC cells; the k_1 , k_a and k_c are the coupling coefficients between the first or the second nearest neighbors, respectively.

Let us define the following quantities

$$\left\{ \begin{array}{l} \tilde{f}_a^2 = f_a^2 / (1 + k_a) \\ \tilde{f}_c^2 = f_c^2 / (1 + k_c) \\ \tilde{k} = k_1^2 / [(1 + k_a)(1 + k_c)] \end{array} \right. \quad (4)$$

The Eq. 3 has the following three solutions

$$\left\{ \begin{array}{l} \frac{1}{F_0^2} = \frac{1-k_c}{f_c^2} \\ \frac{1}{F_{\mp}^2} = \frac{1}{2}(S \pm \sqrt{D^2 + 4\tilde{k}\tilde{f}_a^{-2}\tilde{f}_c^{-2}}) \end{array} \right. \quad (5)$$

with $S = \tilde{f}_c^{-2} + \tilde{f}_a^{-2}$ while $D = \tilde{f}_a^{-2} - \tilde{f}_c^{-2}$.

The system (5) exhibits three equations with three known (F_- , F_0 and F_+) and five unknowns (f_a , f_c , k_a , k_1 and k_c)! When one is dealing with problems having more unknowns than equations, one possible way to act is to perform a parametric study of the system as done in ref. [6], for instance by varying the dimensions of the nose and using the CAD results as a numerical experiment.

Let us define the variable x and y

$$\begin{aligned} x &\equiv (F_-^{-2} + F_+^{-2}) = S \\ y &\equiv (F_-^{-2} - F_+^{-2})^2 = D + 4\tilde{k}\tilde{f}_a^{-2}\tilde{f}_c^{-2}. \end{aligned} \quad (6)$$

Some interesting properties can be drawn from the eq. (6): the variable y as a function of x is a parabola, its minimum coordinates (x_{min} , y_{min}) may give useful information on the lumped circuit parameters

$$\begin{aligned} \tilde{f}_c^{-2} &= \frac{1}{2}(y_{min} + x_{min}^2) / x_{min} \\ k_1^2 &= \frac{1}{2}(1 + k_a)f_c^2 y_{min} / x_{min}. \end{aligned} \quad (7)$$

From the above we readily get k_c and f_c but the structure intrinsically does not allow to get k_a .

The procedure can be outlined as follows:

1. vary the AC frequency modifying the nose¹;
2. "measure" the mode frequencies;
3. plot the points as explained in Eq. (6);
4. find the best fit of the parabola and evaluate f_c , k_c and k_1 as a function of the unknown k_a .

This last unknown can be evaluated realizing by means of the CAD a dual structure: the central cavity is formed by the two half CC's and the side cells are just the central AC halved in two parts. After the evaluation of k_a , one can come back and to calculate all the structure parameters.

As an interesting "consequence" of the method, one gets also a linear fit of the varied f_a as a function of the nose dimensions: this is very important because, as we will see later, the key for optimizing the whole structure is related to this frequency.

A second step consists in realizing a five cell structure by adding the two halves of CC's and by coupling them with the two end cells of the tanks.

The lumped circuit model of this new structure is represented by a new matrix, which for brevity is not shown.

¹Note that f_0 stays unchanged.

By forcing in these equations the coupling constant of the BC, k_c , and the end cell frequency values, by using the mode frequencies, one can build a home made code in Mathematica, based on a variational method, able to find out: the new f_a and f_c of the BC; the first neighbor coupling coefficients between the tank and the BC, k_1^{TB} , and between the cells of the BC, k_1^{BB} ; the second neighbor coupling coefficient between AC's of the tank and AC of the BC, k_a^{TB} . This step needs only one simulation.

The final step is to study the whole system, in order to focus the crucial parameters for the optimum in terms of electric field distribution in the system. We are dealing with a structure of 53 cells, formed by two tanks of 25 cells each one (T1 and T2 respectively) and a BC, this study is not possible for such a big system by using 3D e-m CAD's.

In Fig. 1 it is shown the field behaviour for a structure fed at $\pi/2$ mode in which the BC is designed resorting to the usual procedure: f_a of the BC equal to the f_a of the tanks and the tanks and BC coupled by means of AC cells. It is apparent that the optimum is not yet reached!

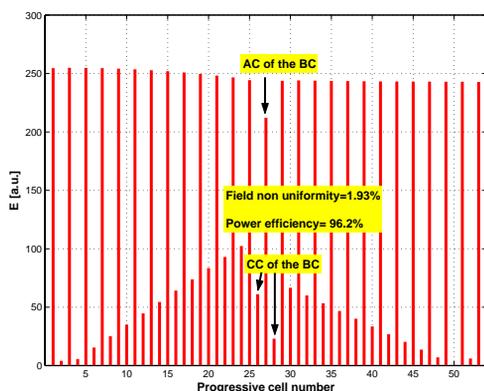


Figure 1: Field behaviour for a SCL module designed resorting to the old procedure.

After the study of the system, one learns:

1. each tank has to terminate in both sides with an end cell: this gives a great stability to the whole system with respect to possible errors in its parameters;
2. after the designing and the optimization of the tanks, the key for reaching the optimum for the whole structure is the value of f_a .

Indeed the numerical analysis shows that the square of the field amplitude standard deviation is a biquadratic function of f_a ; while the power efficiency is a quadratic function of f_a .

After the optimization study, by choosing the optimum value for f_a , one gets, for a structure with T1 and T2 tuned but $T1 \neq T2$, a situation as in Fig. 2.

CONCLUSIONS

In this paper we showed a more reliable and faster procedure to design a module of an SCL. The heart of the procedure

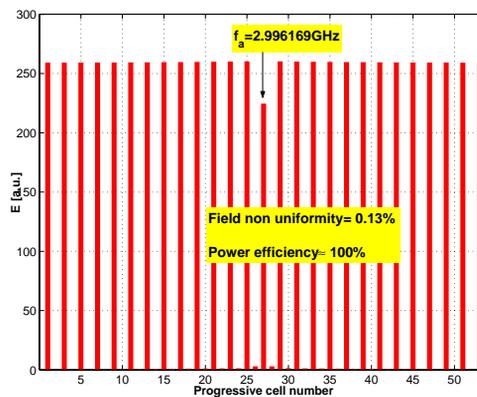


Figure 2: Field behaviour of a SCL module designed by means of the new procedure.

is in a powerful lumped circuit model which provides several tools in order to represent and check any step of the designing.

The procedure foresees also an innovative method to design a BC. Starting from a model able to fully represent the behaviour of the BC, a parametric study of this system gives a parabolic fit, the minimum of which permits the evaluation of all the parameters of this device. From these parameters, by using again a lumped circuit model, one can obtain the BC parameters when it is inserted between the tanks. At this point the possibility of foreseeing the behaviour in a complex structure composed by different device coupled one to each other, permits to focus the crucial quantities in order to have the best performances of the whole coupled system.

We learnt that each tank has to be closed in both sides by an end cell, this gives the maximum stability with respect to errors in the nominal parameters; and also that the keystone for reaching the best performances is to suitably set the AC frequency of the BC.

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