12-12-2000

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N/RÉF: **DAPNIA/SEA/IPHI 2000/69**
V/RÉF:
OBJET: **Design of a Ramped-gradient drift-tube linac**

Design of a Ramped-gradient drift-tube linac

Figures

1. PAPER GOAL

The Ramped-gradient drift-tube linac (RGDTL) is an accelerating structure that allow to match the beam from the low accelerating gradient of a RFQ to a higher gradient structure in which it is easier to control longitudinal beam dynamics. Ramped accelerating gradients in drift tube linac are made possible by the use of post-couplers. Post coupler is a resonant field-stabilization device used in DTL tanks serving the same purpose as the coupling cavities do in CCL and CCDTL structures. The posts, of electrical length $\lambda/4$ are attached to the wall of the tank and protrude in toward the center of the drift tubes. They alternate from one side of the tank to the other, at azimuth angle of ±90 degrees from the stems supporting the drift tubes. They can also be used to achieve a ramped field distribution by rotation of their extremities. They also affect the cavity frequency. To reach the design frequency of the TM010 accelerating mode some other tuning devices are necessary [1].

Such a ramped-gradient DTL stabilizes the field but some of the cavity power is dissipated on the post-couplers to maintain the ramp. The peak power density on post-couplers located on the steepest part of the ramp can exceed by more than 10 times the maximum power density on the tank wall. The post-couplers are necessary excited to maintain such a ramp unless fields without post-couplers already incorporate the same ramp. James H. Billen [2] described a method of detuning only the two end cells to reduce post-couplers excitation in order to minimize post-coupler power. This method works only with a linear ramp, but for a more complicated ramp this approach doesn't work.

This method can be extrapolated. If the tank is fully designed with the good ramp field, the power dissipated on the post-couplers will be minimal, as they will only be excited by mechanical errors, misalignments or others.

The intent of this report is to show the study results concerning the RGDTL simulations, which help to understand the main phenomena in this type of structure.

2. TOOLS

DTLFISH from LANL has been used to simulate a single cell, and MDTFISH for the whole tank. With these axisymetric codes, it's not possible to observe the effects on the field distribution of non-circular structures like the stems and post-couplers. But these codes give the frequency shifts due to the stems and post-couplers, considering them as a perturbation [3]. To generate the cell and the tank designs, we used GENWIN2, which is a DTL generator written in SEA, which allows to design a DTL structure according to field law, phase law, frequency law and other parameters. It automatically creates the input files for SUPERFISH to run it, and extracts the results in order to generate each cell and finally the tank and its file description, which is used by MDTFISH.

As MDTFISH is memory and computation time consuming, our studies have been limited to a 20 and 30 cells tank. Nevertheless, some calculations have been performed with the 50 cells tank of the project IPHI and the results are presented at the end of this paper.

Considering computation time, 0.8 mm mesh size (about 10^{-3} time the wavelength) has been used to simulate the full tanks in MDTFISH, giving a frequency precision of about 0.01 % [4]. The calculation of a single cell has been done with DTLFISH and a 0.3 mm mesh size, giving a frequency precision of about 0.001%.

3. DTL TANK

3.1. Design

The design used is the first 30 cells from IPHI [5]. The resonant frequency is 352.21 MHz, and the main dimensions are showed below.

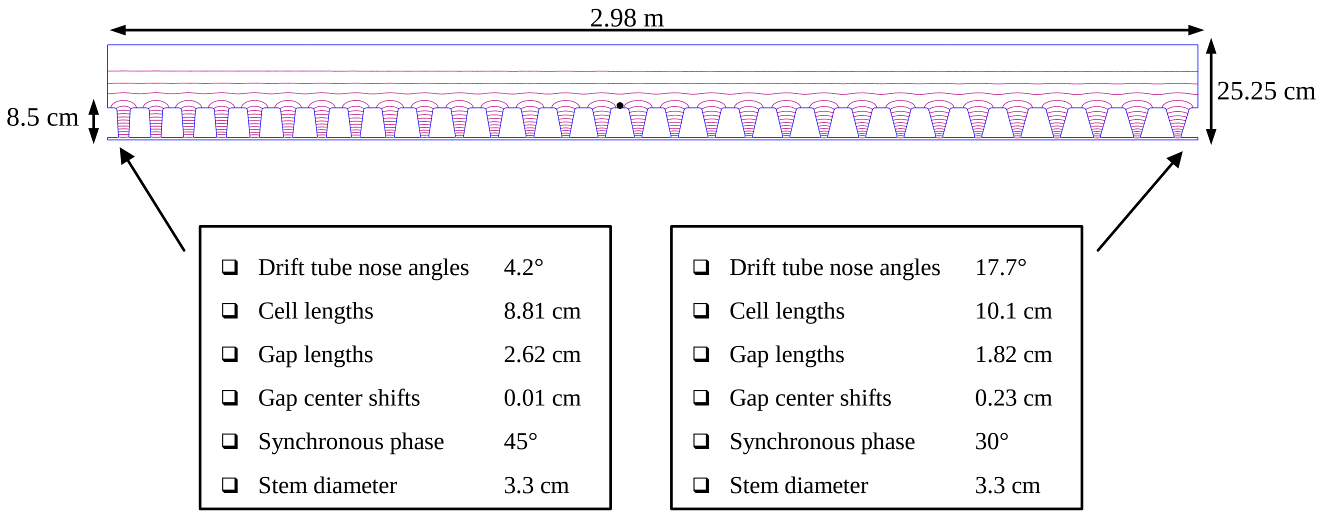

Figure 3-1: Tank design

3.2. Tuning method

3.2.1. Cell

Each cell is independently tuned. The tuning stages are described below. The cell frequency is corrected by taking account the stem frequency shift. Actually, SUPERFISH calculates this shift, but introduces no effect on the field distribution and doesn't tune the cell to the corrected frequency.

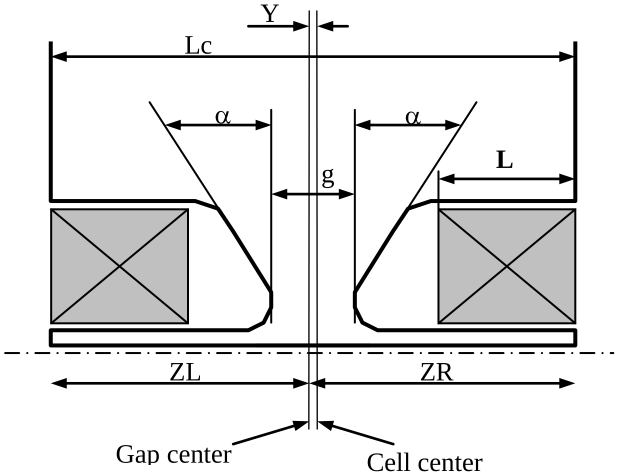

Figure 3-2: Cell design

5 dimensions can be adjusted: g, L_c, ZL, ZR, and α, to reach 5 conditions: $\Delta\phi$ (phase length per cell), ϕ_s (synchronous phase), F_r (resonant frequency), the assigned place for quadrupole, and to keep

Kilpatrick field lower than a defined limit (here 0.9). First, we calculated a symmetric cell and then a non-symmetric cell, to obtain the exact design of the cell.

Tuning steps:

- Adjust g to tune cell.
- Run SUPERFISH and read the field distribution and resonant frequency.
- Calculate $\Delta\phi$ and ϕ_s.
- Adjust L_c to reach $\Delta\phi$
- Adjust ZL or Y to reach ϕ_s.
- Adjust α in order to keep enough space for the L_q length quadrupole.
- Increase α to keep the Kilpatrick field lower than the defined limit.
- Return to first step.

Obviously there are some correlations between each condition. But after 3 or 4 iterations the process converges. It isn't useful to tune the whole tank; as each individual cell is already tuned, the assembly of all the cells should be also globally tuned.

3.2.2. RGDTL

The basic way to change a field distribution shape is to use the relation between the voltage and the frequency [6].

$$\frac{\Delta f(z)}{f_0} \approx \frac{1}{2}\left(\frac{\lambda_0}{2\pi}\right)^2 \frac{V''(z)}{V(z)}$$

By carefully detuning locally some cells a field ramp can be done without changing the tank frequency. Thus, each cell is separately tuned with a different resonant frequency, using the method described below.

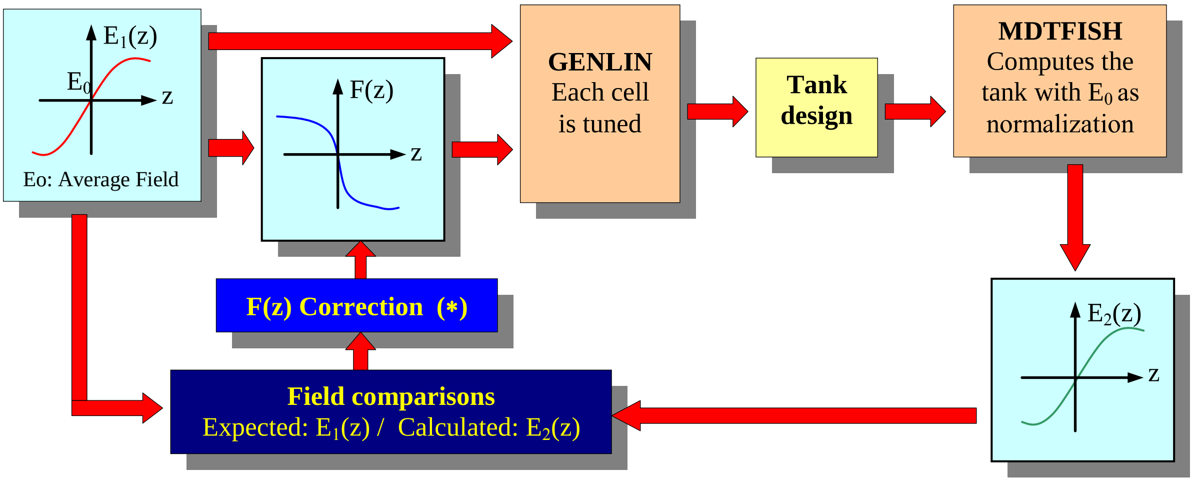

Figure 3-3: RGDTL tuning

(∗): For all the following studies, the step "*F(z) correction*" was not used. The differences between the calculated and the expected field are smaller than 1%. But in a final design, some corrections are necessary because the frequency is calculated from the potential; as the tuning of a cell acts on the gap length, this gap is not kept constant and so the field law is modified and needs to be adjusted.

4. DTL WITHOUT FIELD RAMP

The first stage is to verify the field homogeneity along the structure before to impose any ramp. Three different configurations have been computed.

- DTL1: The 30 cells have exactly the same design; that means no acceleration and no synchronous phase law.
- DTL2 is a classical tank design where the cell geometry (cell and gap lengths, nose angle, electric gap center) changes according to the acceleration and the synchronous phase law (-45° to –36°). But, each cell has been tuned without taking into account the stem frequency shifts.
- DTL3 is similar to DTL2 excepted that each cell has been tuned taking into account the stem frequency shifts.

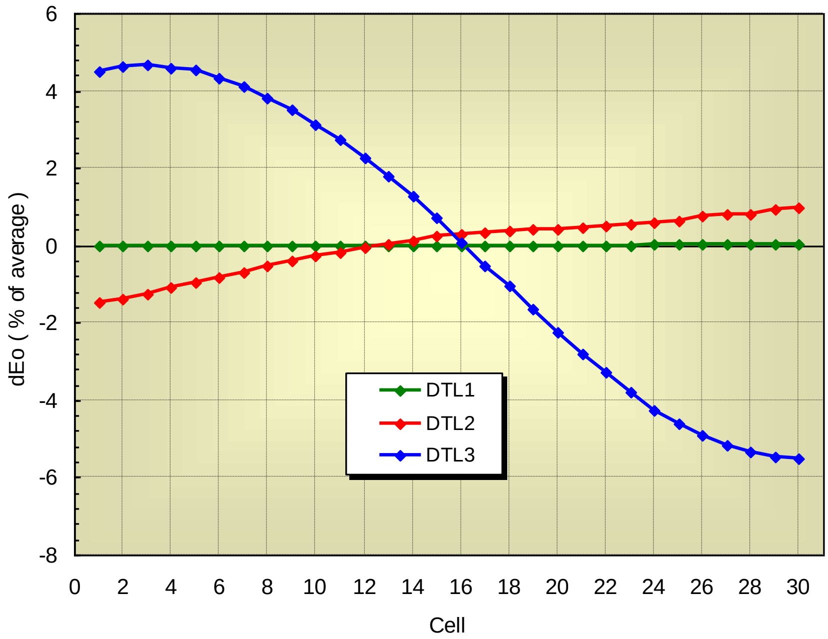

Figure 4-1: Electric field error.

Global tank frequency:
DTL1: 352.254 MHz
DTL2: 352.219 MHz
DTL3: 352.263 MHz

The comparison between DTL1 and DTL2 indicates that the errors are bigger when the structure is not periodic. DTL3 has been calculated taking into account the stem frequency shifts. But, these shifts decrease as to the cell length increases. That means, as SUPERFISH only considers the stems as a perturbation, it doesn’t actually takes into account his frequency shift in the field computation, so that each cell frequency is shifted by a different frequency, resulting in a field law caused by this frequency law. That explains the more important errors. We can verify this interpretation; the figure 4-2 shows that the frequency law giving the field law of DTL3 and the frequency of each cell without the stems are the same.

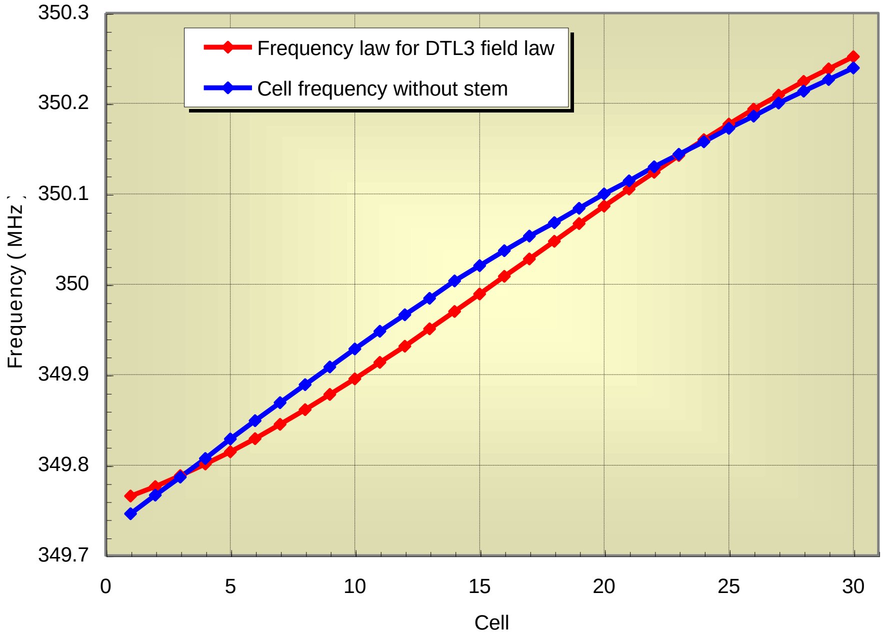

Figure 4-2: Frequency law comparisons.

The two frequency laws are actually the same, thus, the field distribution of DTL3 is due to the frequency shifts induced by the stems. The stem frequency shifts are about 2 MHz.

These three cases show two important points. First, if each cell is individually tuned without taking into account the stem the global tank frequency will be the right one, but the field distribution will not be exactly the expected field distribution. Second, If the cells is tuned taking into account the stem frequency shifts, the field distribution calculated by SUPERFISH will decrease from low energy towards high energy, but the real field should be flat. Therefor, if each cell is tuned without taking into account the stem frequency shifts, field distribution calculated by SUPERFISH will be flat, and the real field will increase from low energy towards high energy.

5. RGDTL

For the RGDTL studies, a tank of 20 cells has been used for two reasons. First, the computation time is lower, and second, the field distribution errors in a flat field case is perfectly compensated by the errors introduced by the stem frequency shifts (these errors become lower than 0.2%).

5.1. Linear field distribution

The classical way to create a linear field ramp is to decrease the first cell frequency and to increase the last cell frequency of the same value, in order to maintain the tank frequency to 352.21 MHz. It results in lower field in cell 1 and higher field in cell 20 with an approximately linear distribution in between. With an opposite sign perturbation of the end cells the field slope is opposed. The tilt sensibility is defined as the difference between these two results divided by the net perturbation applied to the end cells; it represents the tank sensibility in %/Mhz to a perturbation.

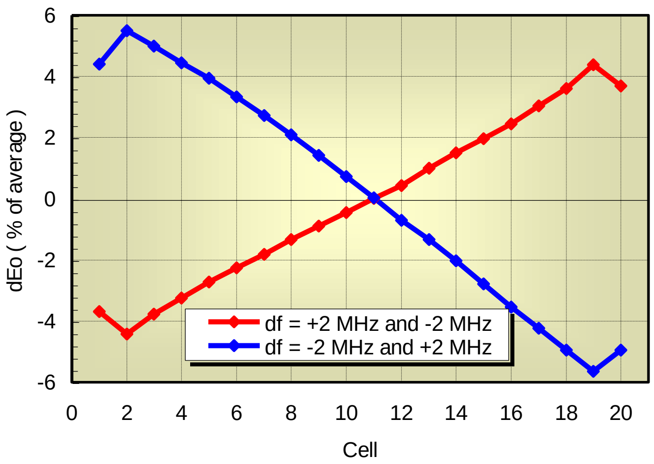

Figure 5-1: Field distribution for two 2 MHz opposite frequency tilts in end cells.

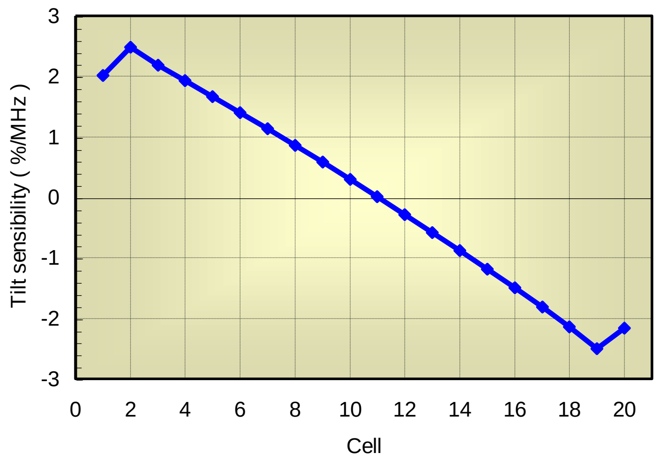

Figure 5-2: Tilt sensibility.

Different perturbations have been represented on Figure 5-3.

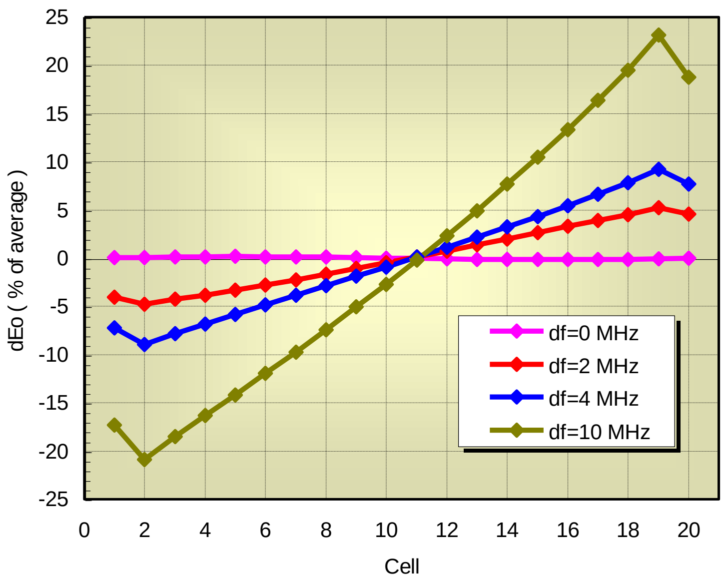

Figure 5-3: Field distribution for different frequency tilts.

We explain the two field distribution tilts to the end cells by the field boundary conditions: $\frac{\partial E}{\partial z}(z=0,z=L)=0$

These results are slightly surprising, because the tank seems less sensible to a frequency perturbation, according to some publications concerning this topic [1][7]. But, for IPHI, with 50 cells, the tilt sensibility will become about ±6.5 %/MHz. That means that, if we want to keep the errors on the field lower than 1%, the frequency tolerance should be 160 kHz, thus the mechanical tolerances will have to be lower than 24 μm, which is very severe. The stabilization by post-couplers is thus absolutely necessary.

5.2. Cubic field distribution

To test some more complicated field distribution shapes and describe them, we use a five-order polynomial with 5 conditions in order to determine the 5 coefficients. The second derivative and thus the frequency law become easier to get.

- $E_0 = E(z=0)$ And $E_1 = E(z=L)$
- $\frac{\partial E}{\partial z}(z=0)=0$, $\frac{\partial E}{\partial z}(z=L)=0$
- $E(z=\frac{L}{2})=\frac{E_0+E_1}{2}$
- The field slope to the middle: $p\frac{E_0-E_1}{2}$,

The p coefficient allows to obtain several field distribution shapes (Figure 5-4). Thus, the frequency laws are calculated from these field distributions (Figure 5-5); then, the 20 cells tanks are generated according to these frequency laws. The field distributions of the tank are compared to the expected field distributions (Figure 5-6).

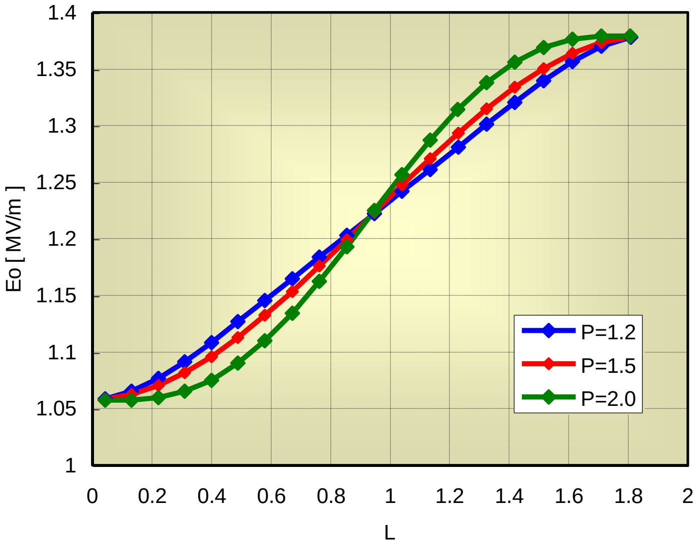

Figure 5-4: Several field distribution shapes.

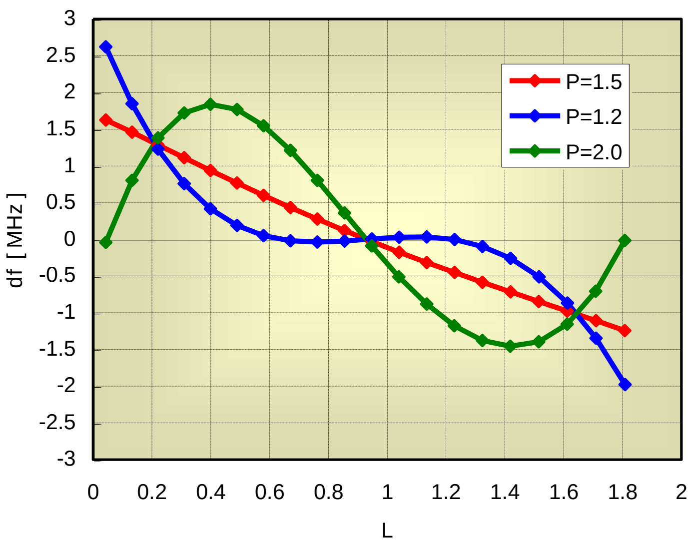

Figure 5-5: Frequency laws.

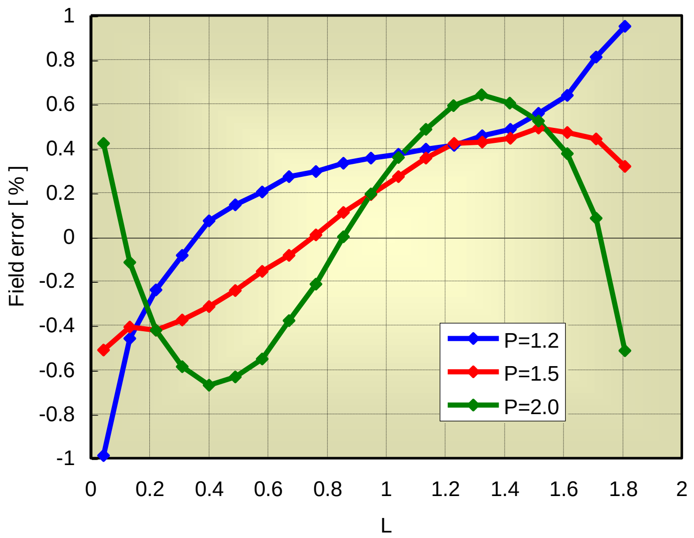

Figure 5-6: Difference between calculated field and expected field.

The errors on the expected field are always lower than 1%. The method works perfectly, probably because the frequency law has no discontinuity. In these examples, we didn't iterate a second correction on the frequency law (figure 3-3), in order to obtain more exactly the expected field.

6. IPHI EXAMPLE

6.1. Flat field simulation

The DTL of IPHI project is a RGDTL of 50 cells with a field ramp of 1.08 MV/m to 1.75 MV/m. Nevertheless, the structure has been just simulated with a constant field of 1.4 MV/m all along the DTL, in order to compare two designs, with or without stem frequency corrections.

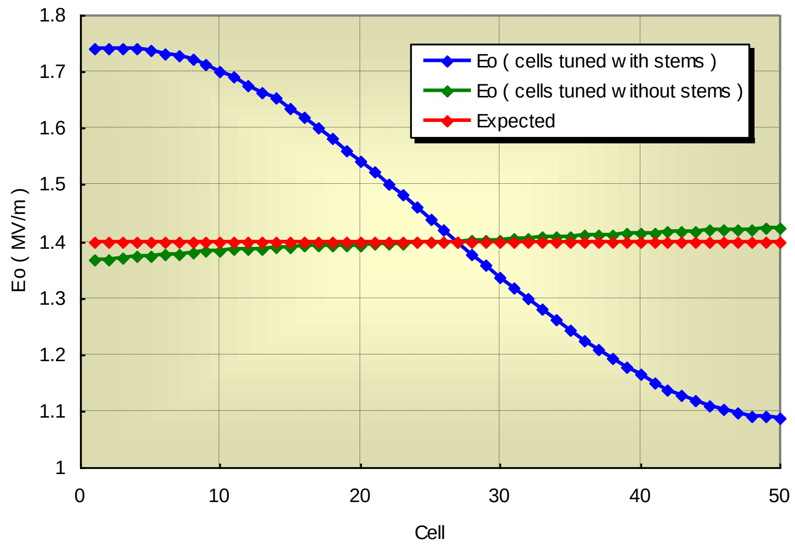

Figure 6-1: Field distribution in IPHI from SUPERFISH.

As explained in chapter 4, when we tune each cell taking into account the stem frequency shifts, the field distribution computed by SUPERFISH decreases from the low energy toward the high energy. But the real field is flat. Inversely, When we tune each cell without taking into account the stems, the field distribution computed by SUPERFISH is flat (±2%), but in fact, the real field increases from the low energy and towards high energy end.

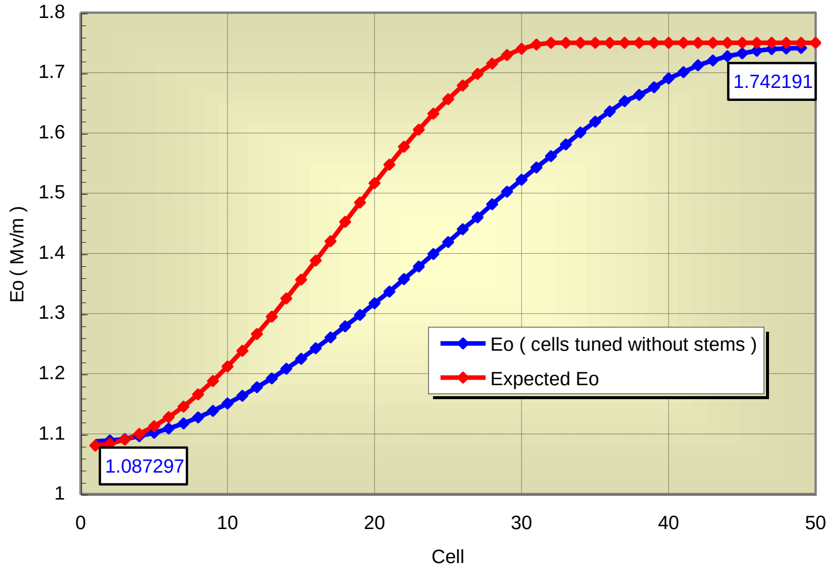

Figure 6-2: Real field (cells tuned without stem) compared to expected field.

That means that, for the IPHI case designed without taking into account the stems, the field distribution obtained begins and ends exactly at the wished field values. It is very lucky and interesting. Obviously, the shape is not exactly the right one, but we could decide to change the field law in order to simplify the design method.

6.2. Accuracy

If we observe with more accuracy the result of the simulation without the stem frequency shifts (Figure 6-1), we can see that the field distribution is not exactly flat, the errors are within ±2% (Figure 6-3).

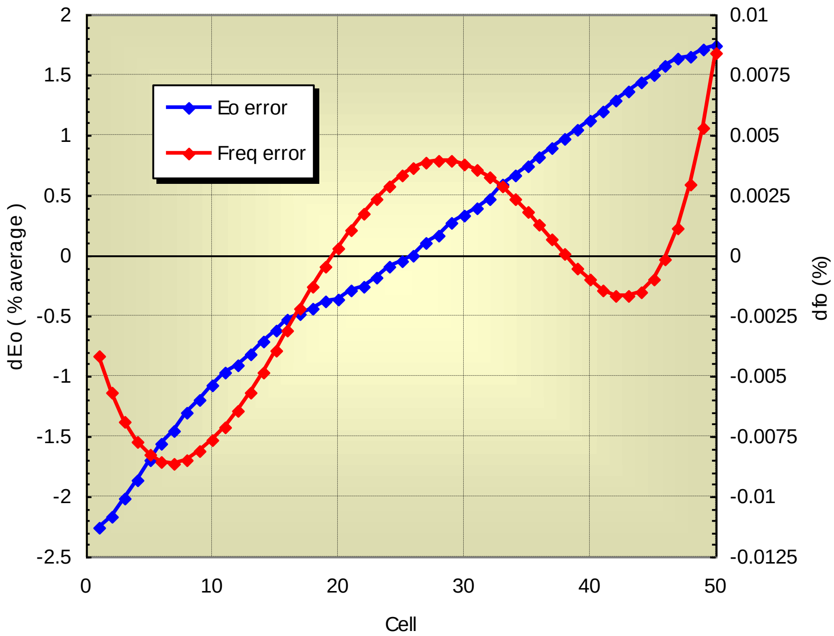

Figure 6-3: Field error and frequency error.

The curve “frequency error” is the frequency law calculated, which would induce these field errors, if the field distribution was perfectly flat. This frequency oscillates around ±0.01%, which is the expected frequency precision for a 0.8 mm mesh size. It is nevertheless premature to conclude that the errors on the individual cell frequencies are only cause of the field errors. Before doing so, we would have to simulate more accurately the structure, which is currently not possible for mesh size raison.

7. CONCLUSIONS

The results clearly show that it’s possible to design a tank in order to obtain a defined field distribution. But, SUPERFISH codes do not allow to know if the power losses on the post-couplers will be lower if the field is already incorporated in the whole tank design. A 3D study will be probably necessary to verify this point. But, to verify it a prototype will be the best way to understand all the phenomena. The structure sensibility to the errors increases very quickly when the number of cell increases. It’s also clear that the stem effects are very important and that we can’t neglect them in a RGDTL design nor in a flat field DTL. It is also noteworthy that now the computer power allows to simulate with a good accuracy the full tank (2D), in order to verify the designs.

8. REFERENCES

[1] James H. Billen and Alan H. Shapiro, “Post-couplers stabilization and tuning of a ramped-gradient drift-tube linac”. Proc.: Linac88 conference.

[2] James H. Billen, “Analysis of measured Post-coupler fields in a ramped-gradient drift-tube linac”. Proc.: Linac88 conference.

[3] James H. Billen and Lloyd M. Young, “SUPERFISH Documentation”. Ref: LA-UR-96-1834.

[4] Didier URIOT, “Design et étude électomagnetic”. Internal memo, ref: DSM/DAPNIA/SEA/IPHI 99/49.

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[6] Pacal Balleyguier, “Obtention de la loi de tension d’IPHI le long du RFQ”. Internal memo, ref: B3/DIF/DPTA/SP2A N° 54/99.

[7] James H. Billen, J. A. Garcia, J. M. Potter, and G. Spalek, “A 3λ/4 Post-coupler for drift-tube linacs”. IEEE Trans. Nuc. Sci., Vol NS-32, N°5, oct. 85.