EFFECT AND CONTROL OF THE DEE TO DEE COUPLING CAPACITANCES

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Summary

The effect of the capacitances between the dees of a cyclotron is negligible or stabilizing if the dees are operating in 0- or π-mode, respectively. The effect becomes critical in compact three sectors Superconducting Cyclotrons where the dees are operating in modes different from the 0- or π-mode (120 degrees difference in phase). In this paper we present a compensating system design, which can compensate completely this effect without a strong influence on the RF cavity characteristics.

The phase difference between the current in the coupler and the current oscillating in the cavity is, as we show in ch.1, the fundamental criteria for a decision on utilizing a compensating system.

In ch.2 we present how the system in principle works and in ch.3 we show how one can calculate the main parameters, followed by indications how to optimize the compensating system.

In ch.4 we give some practical hints how to use the system and to avoid too elaborated calculations.

1 - Effects of the dee to dee capacitances

It is very important to understand why the cyclotron is so sensitive to the capacitances between the dees to be able to predict the cyclotron behavior and to know when it is necessary to utilize a compensating system.

Besides its normal coupling towards its power amplifier, each dee has a competitive capacitive coupling towards the other dees (Fig.1.1). This effect of the dee to dee capacitances[1,2] gives a phase difference (β) between the current arriving from the power amplifier and the current oscillating in the RF-cavity.

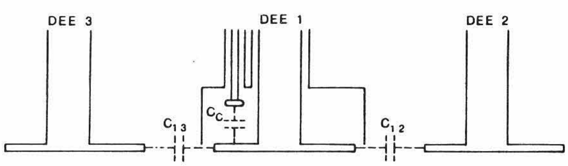


Fig.1.1 - Competitive couplings of a dee

This phase can be calculated using the law of Kirchhoff on the currents passing across the capacitances between the dees and the current passing the coupling capacitance C_c. With the dee voltage $\hat{V}_D$ and the coupling voltage $\hat{V}_c$ we get:

$$\beta = \arcsin \frac{\sqrt{3}}{2} \cdot \frac{(C_{12}-C_{13})}{C_c} \cdot \frac{\hat{V}_D}{\hat{V}_c} \qquad (1.1)$$

which is the necessary phase difference on the coupler capacitance C_c to adjust for the effect from the unequilibrated capacitances between the dees.

Because of the competitive couplings each cavity exchanges power with the other dees, i.e. each power amplifier feeds partly all the cavities.

The competitive couplings give theoretical limits of cyclotron operations but also lower practical limits like power consumption, sparks etc. given by the reflexion in the coupler.

It should be pointed out that the capacitances between the dees can be used in a positive way, measuring the movement of the distances between the dees.

In fact if one feeds power into one RF cavity, giving the voltage V_1 on the dee, the other two dees are showing the voltages V_2 and V_3 respectively; as this effect can be analyzed with the help of a computer code like SPICE[3], this gives a good measurement of the capacitances between the dees. These capacitances can also be calculated with three dimensional computer codes[4]; it is therefore possible to follow up this measurement calculating the geometrical changes following the dee movements at any power level.

2-The compensating system

From eq.(1.1) one realizes that if the capacitances are too big and/or badly equilibrated, the cyclotron can not operate in the wanted mode. It is in this case necessary to introduce a compensating system.

We also see that the phase β is directly coupled to the difference between the capacitances from dee nr.1 to the other dees and not from the absolute values of these capacitances, i.e. it is enough to compensate the capacitive difference independently from the actual value of these capacitances.

Compensation means therefore to make the capacitive effect between the dees equal, because in this way the reactive powers exchanged between the dees are equal for each dee.

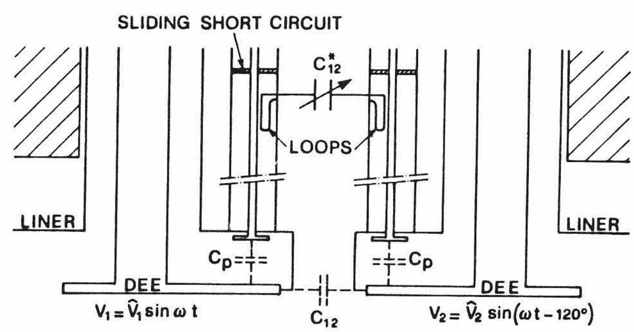
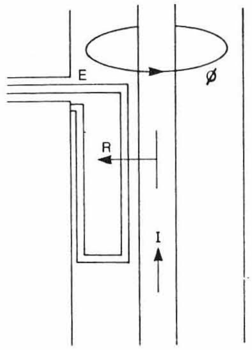


Fig.2.1 - Simplified compensation system

As an example in the Milan K800 superconducting cyclotron, with internal ion source, compensation could be achieved fitting into the holes symmetrical to the coupling capacitors a variable length coaxial line, coupled capacitively to the dee and ended with a short-circuit (where the high voltage of the dee is changed to high current i.e. strong magnetic field, in the short circuit), around λ/4 distance away from the dee (Fig.2.1). The parasitic coaxial lines can then be coupled together by inductive loops.

The loops have a self inductance too high to pick up enough current with reasonable size, power consumption, voltage etc. (Fig.2.2).

If A is the area of the loop and the peak voltages V_D on the dees are considered equal, the inductance we must have in each loop is:



$$L = \frac{(\mu_o A \hat{I})^2}{2V_D^2 C_{ij}(2\pi R)^2} \quad (2.1)$$

Fig.2.2 - The inductive loop

where C_{ij} represents the capacitive effect we want to compensate. Inserting a capacitor between each pair of loops, in parallel with the capacitance between the respective dees but 180 degrees different in phase, we create a flux of reactive power counteracting the reactive power exchange across the capacitances between the dees i.e. we recycle the reactive power in a closed circuit. We can therefore say that the capacitors C^* between the coaxial lines are the complements to the capacitive effects we want to compensate of the capacitances between the dees:

$$C^* = \frac{1}{2\,\omega^2 L} \quad (2.2)$$

An optimized system can make the dees independent from each other, that is compensate the capacitances between the dees at a zero capacitive effect level (this is also called to neutralize).

With this system compensation can be achieved at any reasonable level, even an over compensation can be reached giving an inductive effect between the dees. It is possible to add capacitances by simply turning the loops between two coaxial lines upside down.

The parasitic coaxial line with its dee-pickup can be described with the help of matrixes as follows:

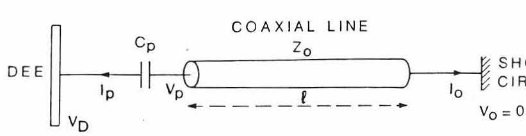


Fig.2.3 - The parasitic coaxial line

$$\begin{pmatrix} V_D \\ I_p \end{pmatrix} = \begin{pmatrix} 1 & \frac{1}{j\omega C_p} \\ 0 & 1 \end{pmatrix} * \begin{pmatrix} \cos kl & jZ_o \sin kl \\ \frac{j}{Z_o}\sin kl & \cos kl \end{pmatrix} * \begin{pmatrix} V_o \\ I_o \end{pmatrix}$$

$$V_D = jI_o(Z_o \sin kl - \frac{\cos kl}{\omega C_p}) \quad (2.3)$$

$$I_p = I_o \cos kl \quad (2.4)$$

$$kl = \arcsin \frac{V_D}{I_o Z_T} + \arcsin \frac{1}{\omega C_p Z_T} \quad (2.5)$$

$$V_p = jI_o Z_o \sin kl \quad (2.6)$$

$$Z_T = \sqrt{Z_o^2 + \frac{1}{\omega^2 C_p^2}} \quad ; \quad \lambda = \text{wave length}$$

$$Z_o = \text{charact. impedance} \quad ; \quad k = \frac{2\pi}{\lambda}$$

From eq. (2.4) and (2.6) we see that the current and voltage distributions in the coaxial line are purely sinusoidal with a maximum and minimum respectively at the short circuit. From eq.(2.3) we learn that at a specific frequency we have I_o and l as the only free parameters. We can therefore choose the optimal short circuit current (optimal induced current into the loops) by simply moving the short circuit. From eq.(2.3) and (2.5) we also see that there are two possible positions for the short circuit, one with equal sign on the voltage on both side of the dee-pickup capacitance C_p (0-mode position) and another one with different voltage sign (π-mode position).

The parasitic coaxial lines and their pickups effect the cavity as a capacitance in parallel, so that the influence on the frequency of each cavity can, by using eq.(2.3), be written as:

$$\Delta f = \frac{-\,C_p \cdot f}{2C(1-\omega C_p Z_o \,\mathrm{tg}\,kl)} = \frac{\hat{I}_o \cos kl}{4\pi C V_D} \quad (2.7)$$

3-Optimizing the compensating system

Some basic considerations must be made in order to understand how the system works.

The current in the dee-pickup coaxial line should be kept small for several reasons (power consumption, frequency change of the RF-cavity, dimensions, cooling problems etc.) but the currents induced, by the loops, into the parasitic coaxial lines could then be of the same order of magnitude as the fundamental currents given by the dees. As these currents have phases different from the fundamental ones this can cause the system to run with phases different from the ideal ones. It seems therefore necessary to increase the fundamental currents to reduce these phase errors.

At this point it is evident that a detailed analysis is necessary in order to optimize the system.

Here and in the following we assume that the system is able to completely compensate the capacitive effect between the dees; this must be close to the reality if the system should work.

Let us now take a look at the current in the parasitic coaxial line nr.1 which is composed of three different currents, the fundamental I_1 given by the dee nr.1 and the two currents I_{12} and I_{13} which are the currents induced into the line by the two loops.

We begin with answering two important questions:

- At which phases are I_{12} and I_{13} acting versus I_1?

This question can be answered by taking two parasitic coaxial lines with 120 degrees short circuit currents phase difference. On the loops, in the line connecting the parasitic coaxial lines voltages are induced with a phase difference of 120 degrees. At a certain time a maximum voltage drop over a capacitor C^*_{ij}, creates a maximum current through it 90 degrees later. This current has a maximum in the loop where the current is arriving and at the same time a minimum in the loop it is leaving. For reasons of symmetry it follows that the currents I_{12} and I_{13} are induced into the coaxial line with ±30 degrees difference versus I_1.

– Are the currents I_{12} and I_{13} positive or negative versus I_1?

To answer this question let us look at the current passing over the dee-pickup capacitance C_{p1} of the parasitic coaxial line nr.1. Without the loops in the coaxial line a certain current pass over C_{p1} which, as it is capacitive, has the same direction as the currents passing from dee nr.1 to the other dees. To compensate these currents one should counteract (i.e. reduce) the current over C_{p1}. This current is given by the voltage drop across C_{p1};we should therefore reduce this. This can be done by increasing the voltage V_{p1} on the dee-pickup i.e. increasing the current in the short circuit of the parasitic coaxial line in the case of 0-mode position and reducing the voltage V_{p1} and the short circuit current in the case of π-mode position, (see ch.2). If we reduce the reactive power passing across the capacitance C_{p1} with the same amount as the reactive powers that we want to compensate, (passing from dee nr.1 to the other dees) then we have reached our goal. We conclude therefore that the currents I_{12} and I_{13} should be added to I_1 at 0-mode position and subtracted in the π-mode position.

We assume from now on that we work in 0-mode position as here the phases in the coaxial lines are smaller and therefore the system works somewhat better in this position, also if the two solutions are very close together. It should be noted that the π-mode position gives a longer coaxial line, which could be useful from a constructional point of view.

We choose the parasitic coaxial line coupled to dee nr.1 as an example in the following calculations. By changing the indexes in a cyclic order the formulas are the same for all the parasitic coaxial lines.

From the previous remarks it follows that the total current in the parasitic coaxial line nr.1 is:

$$I_{T1} = \hat{I}_1\sin\omega t + \hat{I}_{12}\sin(\omega t+30)+\hat{I}_{13}\sin(\omega t-30) \qquad (3.1)$$

$$I_{T1} = \hat{I}_{T1}\sin(\omega t + \arcsin\frac{\hat{I}_{12}-\hat{I}_{13}}{2\,\hat{I}_{T1}})$$

$$\hat{I}_{T1} = \sqrt{\hat{I}_1^2+\hat{I}_{12}^2+\hat{I}_{13}^2+\hat{I}_{12}\hat{I}_{13}+\sqrt{3}\hat{I}_1(\hat{I}_{12}+\hat{I}_{13})}$$

Using eq.(2.6) and assuming $V_1 = \hat{V}_1\sin\omega t$ on the dee nr.1, we get the compensating voltage over C_{p1} as:

$$(V_1-V_{p1})-(V_1-V'_{p1}) =$$

$$= Z_o\sin kl(\hat{I}_{12}\sin(\omega t+30)+\hat{I}_{13}\sin(\omega t-30)) =$$

$$= \hat{V}_{cp}\sin(\omega t + \arcsin\frac{\hat{I}_{12}-\hat{I}_{13}}{2\sqrt{\hat{I}_{12}^2+\hat{I}_{13}^2+\hat{I}_{12}\hat{I}_{13}}}) \qquad (3.2)$$

Using an electrostatic approach, i.e. assuming that at a given time the voltage on a dee (V_i) is constant and equal all over the dee, we get that the charge on each dee can be written as:

$$\begin{cases} Q_1 = (V_1-V_2)\cdot C_{12}+(V_1-V_3)\cdot C_{13} \\ Q_2 = (V_2-V_3)\cdot C_{23}+(V_2-V_1)\cdot C_{12} \\ Q_3 = (V_3-V_1)\cdot C_{13}+(V_3-V_2)\cdot C_{23} \end{cases} \qquad \begin{cases} V_1 = \sin\omega t \\ V_2 = V\sin(\omega t-120) \\ V_3 = V\sin(\omega t+120) \end{cases}$$

It follows that the voltage drop from dee nr.1 to the other dees is:

$$V' = \hat{V}'\sin(\omega t + \arcsin\frac{C_{12}-C_{13}}{2\sqrt{C_{12}^2+C_{13}^2+C_{12}C_{13}}}) \qquad (3.3)$$

$$\hat{V}' = \frac{\hat{V}\sqrt{3\cdot(C_{12}^2+C_{13}^2+C_{12}C_{13})}}{C_{12}+C_{13}}$$

(C_{ij} means the capacitances corresponding to the capacitive effect we want to compensate i.e. they mean the actual capacitances between the dees only if one calculates the system for compensation at zero level, i.e. neutralization.)

At compensation the phase of the voltage drop across C_{p1} is equal to the phase of the total voltage drop between dee nr.1 and the other dees. Obviously also the compensating reactive power passing C_{p1} should be equal to the reactive power one wants to compensate, passing between dee nr.1 and the others.

We have now that the difference between the reactive power passing the capacitance C_{p1} with and without the inductive loops should be equal to the reactive power one wants to compensate. These relations gives us the currents $\hat{I}_{12}$ and $\hat{I}_{13}$ as:

$$I_{13} \simeq \frac{\sqrt{3}V_D}{Z_o\sin kl}\frac{C_{13}}{C_{p1}} \quad ; \quad \hat{I}_{12} = \frac{C_{12}}{C_{13}}\hat{I}_{13} \qquad (3.4)$$

At the beginning of this calculation we assumed that the system would completely compensate the disturbing capacitances between the dees, but from equation (3.4), it seems this can not be achieved because the total current in a parasitic coaxial line has a phase different from the fundamental one given by the dee (eq.(3.1)). We would therefore not be able to completely compensate the capacitive effect, being different the phases of the voltages across the capacitances C_{ij} and their complements C^*_{ij}.

Fortunately it is easy to overcome the problem, compensating this phase difference by unbalancing the inductances on each side of a capacitor C^*_{ij}. This can be done by varying the area of the loops and/or the total currents in the coaxial lines.

Particularly, looking at Fig. 3.1, the voltage drop across the capacitor C^*_{ij} can be written:

$$E' = \hat{E}_{12}\sin(\omega t+60+\alpha_1)-\hat{E}_{21}\sin(\omega t-60+\alpha_2) =$$

$$= \sqrt{\hat{E}_{12}^2+\hat{E}_{13}^2+2\hat{E}_{12}\hat{E}_{21}\sin(\alpha_1-\alpha_2+30)}\,\cos\omega t \qquad (3.5)$$

where α_i are the current phases in the parasitic coaxial lines, eq.(3.1).

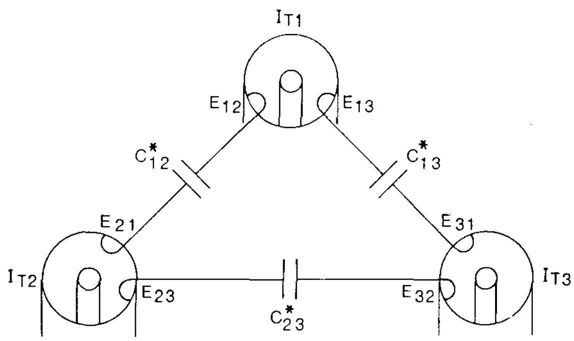


Fig.3.1 - Loop region of the compensating system

The reactive powers passing the capacitors C_{ij} are at complete compensation equal to the reactive powers we want to compensate exchanged between the dees:

$$\begin{cases} Q_i = \dfrac{\hat{V}'^2}{2}\,\omega C_{ij} \\ Q_i^* = \dfrac{\hat{E}'^2}{2}\,\omega C_{ij}^* \end{cases} \Rightarrow \hat{E}' = \hat{V}'\sqrt{\frac{C_{ij}}{C_{ij}^*}} \qquad (3.6)$$

As the phases and the reactive powers over the capacitors C_{ij}^* must be equal with the phases and reactive powers created by the capacitive effect we want to compensate, we get from eq. (3.5) and (3.6):

$$\begin{cases} \hat{E}_{12} = \hat{V}'\sqrt{\dfrac{C_{12}}{C_{12}^*}\cdot\dfrac{\cos(60-\alpha_2)}{\cos(\alpha_2-\alpha_1-30)}} \\ \hat{E}_{21} = \hat{V}'\sqrt{\dfrac{C_{12}}{C_{12}^*}\cdot\dfrac{\cos(60+\alpha_1)}{\cos(\alpha_2-\alpha_1-30)}} \end{cases} \Rightarrow \frac{\hat{E}_{12}}{\hat{E}_{21}} = \frac{\cos(60-\alpha_2)}{\cos(60+\alpha_1)} \qquad (3.7)$$

We can now calculate the induced loop voltages E_{12} and E_{21}, using the equations (2.1) and (2.2) which gives (if R is considered constant):

$$\begin{cases} L_{e12} = \dfrac{(A_{12}\hat{I}_{T1})^2}{\omega^2 C_{12}^*(A_{21}^2\hat{I}_{T2}^2 + A_{12}^2\hat{I}_{T1}^2)} \\ L_{e21} = \dfrac{(A_{21}\hat{I}_{T2})^2}{\omega^2 C_{12}^*(A_{12}^2\hat{I}_{T1}^2 + A_{21}^2\hat{I}_{T2}^2)} \end{cases}$$

$$\Rightarrow \begin{cases} \hat{E}_{12} = V'\omega^2 L_{e12}\sqrt{C_{12}C_{12}^*} \\ \hat{E}_{21} = V'\omega^2 L_{e21}\sqrt{C_{12}C_{12}^*} \end{cases}$$

which gives us the same ratio as in (3.7):

$$\frac{\hat{E}_{12}}{\hat{E}_{21}} = \frac{A_{12}^2\hat{I}_{T1}^2}{A_{21}^2\hat{I}_{T2}^2} = \frac{\cos(60-\alpha_2)}{\cos(60+\alpha_1)} \qquad (3.8)$$

If we insert eq.(3.1) and (3.4) in eq. (3.8) one gets the necessary $A_{ij}\hat{I}_{Ti}$ ratio for each loop pair which gives a perfect compensation.

One can always use the same formulas, but, choosing to add capacitive effects, one has to change sign of the induced voltages, turning the loops.

4-Practical considerations

Using all the given formulas, it is possible to optimize a compensating system, according to a number of design criteria, which are strongly dependent from the machine at which we want to apply the system.

Looking at the machines with a central region designed for internal ion source, the capacitances between the dees are normally in the region of some tenth of a picofarad (MSU K500 ; Texas A and M) with a capacitance difference of the same order, which gives a reactive power exchanged between the dees much larger then the coupling reactive power. As the capacitances between the dees are very unequilibrated, a compensating system is necessary. A system working at a medium capacitive effects level would be preferable, as in this case the size and cost of the capacitors would go down considerably, together with an overall reduced construction complexity.

For bigger capacitances, it could be necessary, to develop a symmetric multi loop combiner, to reduce the necessary current in the short circuits and the dissipated power in the parasitic coaxial lines.

Nevertheless, before designing a complicated system it is much better to try to reduce considerably the capacitances between the dees, designing an internal ion source, considering the capacitive effect problem.

Some calculations has been made considering a compensating system working also during a spark, i.e. keeping the two operating cavities in phase and at full power during a spark. This in principle can be done, but we are convinced that a shutdown system for all the cavities at a spark should be foreseen. In fact a spark in the central region, which normally has the lower voltage holding capability, creates an ion plasma which very often causes another cavity to spark a short time after the first one[5].

Conclusions

We have developed a compensating system which, giving a small reduction of the frequency range of the RF-cavities, compensate the unequilibrated capacitive effect between the dees. In this way a stable operation of the cyclotron is assured, from outside the cyclotron magnet, when the phases between the dees are different from 0 or 180 degrees. Nevertheless, because one year ago the idea to use an internal ion source for the Milan K800 cyclotron was abandoned for an external source with axial injection, a new central region has been developed, looking carefully at the dee to dee capacitances problem[4]. As a consequence, a central region with capacitances of the order of less than 0.01 pF has been designed and so the neutralizing system we present in this paper is no more necessary for the Milan machine, therefore its development was stopped at the level of a preliminary design.

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