POWER COUPLERS: SOURCES AND CONSEQUENCES OF MISMATCHES

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1. Coupling and beam current errors or unusual operational requirements have the consequence that power couplers of superconducting cavities most often work in a non matched state. This situation is analysed in using the equivalent circuit approach and in progressing from simpler to more complex cases.

1 Introduction

For this session on couplers no review talk is programmed. Laboratories shall themselves report on their recent developments. But the CERN couplers have already been described in detail and I have been asked to discuss more general coupler related questions in taking CERN construction as paradigm.

A question which then comes up concerns power couplers for superconducting (sc) cavities. Although such couplers are normal conducting devices we often find them much more difficult to operate than similar constructions on copper cavities. The LEP couplers for copper- and sc cavities respectively are an example.

This difficulty has two reasons which are interconnected. A first is that we rarely can operate such couplers under ideal matched conditions. Part of the responsibility for this situation is in our own camp. The present technology of multi-cell sc cavity construction results in a mediocre field flatness between cells and hence in a considerable scatter of the coupling external Qs within a lot of cavities.

But in addition accelerators often miss (or exceed) originally announced beam currents by factors and that fully reflects back on the load 'seen' by the coupler to a sc cavity where wall losses are negligible.

Thus too often power passes through the coupler in the form of a partial standing wave with locally much higher fields than in the 'flat' matched case and here a second reason of difficulties specific to the sc case comes in:

Our couplers need a warm-cold transition piece bridging the thermal gap between the cavity and the room temperatur ceramic vacuum window at the coupler input. Gas released from the window by RF-heating [1] is cryo-pumped into this piece and, adsorbed to its wall, enhances there the electron secondary emission coefficient (SE).

Higher RF-fields at a given power transfer and enhanced SE in combination are the cause of our main problem: We encounter more levels of resonant RF discharges (multipacting) than in conventional copper systems and these levels are more difficult to condition, have even (because new gas has been adsorbed) the tendency to reappear after a period of operation, an effect called 'deconditioning'.

A coupler talk is not the place to discuss multipacting in detail (but see [2]). However, in putting now the emphasis on conditions of *mismatch*, it appears worthwile to have another look on beam-loading of a sc cavity.

2 Generator-cavity-beam-interaction

2.1 Equivalent circuits

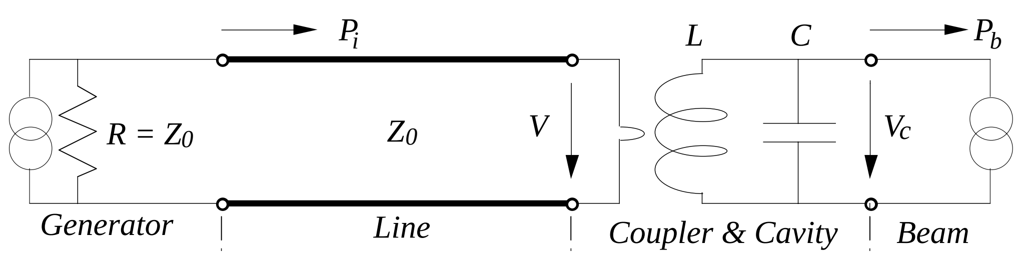

Figure 1: The basic elements of an accelerating station.

If we want to simplify an accelerating station to its essential parts we find five components: A RF *power-generator* with internal resistance *R*, a *transmission line* (the coupler line) with wave-impedance Z_0 from the generator to a *coupler proper*, a *cavity* and a *beam*. The circuit above shows these components. The generator is represented by its Helmholtz equivalent and it has been assumed that the transmission line is source-matched: $Z_0 = R$. It transports the incident (generator) power P_i to the coupling device which here is thought to be inductive (although in reality we prefer capacitive 'probe' coupling). The cavity is a parallel, zero loss *LC*-resonator with resonance frequency $f_c = \omega_c/(2\pi)$, $\omega_c = 1/\sqrt{LC}$ and $\omega_c C = 1/(R/Q)$ and the beam a current source, injecting the RF beam current I_b into the resonator.

At frequencies near to f_c the coupler acts as a step-up transformer i.e. looking from the resonator to the generator one sees a source-matched "abstract" transmission line with a *higher* characteristic impedance Z_e but carrying the *same* power P_i and we can simplify the circuit as outlined below :

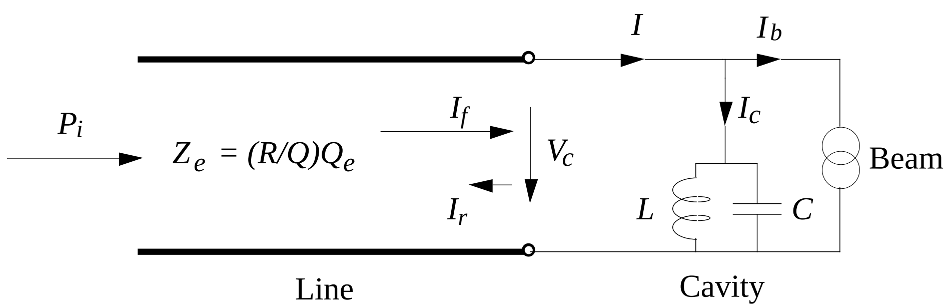

figure 2: Simplified circuit diagram of beam loading

In a 'thought experiment' where the cavity oscillates with an accelerating voltage V_c (which we will call *cavity voltage*) and a stored energy *U* but the generator's source current is switched off, the cavity would loose the power P_e to the generator and the relations hold :

$$\omega U/Q_e = P_e = V_c^2/(2Z_e)$$

but

$$V_c^2 = 2\omega U(R/Q)$$

thus

$$Z_e = (R/Q)\,Q_e \; . \qquad (1)$$

Note, that in a group of cavities fed via a power divider from a single amplifier all cavities can be reasonably expected to receive the same power P_i. But due to *coupling errors* the wave impedances Z_e of their individual 'abstract' feed lines will be different and so also the amplitudes of their forward currents I_f (and forward voltages $V_f = Z_e I_f$) :

$$I_f = \sqrt{2P_i/Z_e} \; .$$

But at this moment we will concentrate on only one cavity with the aim to calculate its accelerating voltage V_c as a function of its forward current I_f and the RF beam current I_b . At our disposal are the following two equations :

$$Z_e I_f + Z_e I_r = V_f + V_r = V_c \qquad (2)$$

and

$$I_f - I_r = I = I_c + I_b = V_c/Z_c + I_b \; . \qquad (3)$$

Note, that V_f, V_r, I_f and I_r are the (complex) amplitudes of waves, measurable only with the help of directional couplers, whereas I_c and I_b are circuit currents in the proper sens.

$Y_c = 1/Z_c$ is the *susceptanc*e of the *LC*-resonator. With the generator frequency f_g and the resonator's resonance frequency f_c :

$$Y_c = 1/Z_c = j\left(\frac{f_g}{f_c} - \frac{f_c}{f_g}\right)\omega_c C \approx j\,2\,\frac{f_g - f_c}{f_c}\,(R/Q)^{-1} \; . \qquad (4)$$

It is instructive to compare a detuning (f_g - f_c) to the loaded bandwidth $\Delta f = f_c/Q_e$ of the cavity. We therefore define a *normalized detuning d* by

$$d = (f_g - f_c)/(\Delta f/2) = 2(f_g - f_c)(Q_e/f_c)$$

and with (4)

$$d = -j\, Z_e / Z_c \tag{5}$$

Dividing now equ. (2) by Z_e and adding the result to equ. (3) we find :

$$2\, I_f = \frac{V_c}{Z_e} + \frac{V_c}{Z_c} + I_b \quad . \tag{6}$$

2.2 Phasor diagrams

Equ. (6) is well suited to visualize the problems of tuning and matching graphically. All its four terms are complex current phasors and so, in a complex current plane, one can represent equ. (6) by a phasor diagram :

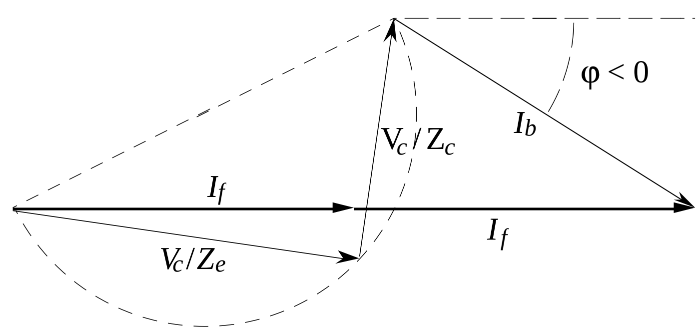

Figure 3: Phasor diagram of beam loading

In the diagram above, by an appropriate choice of the time zero, the forward current I_f is on the real axis of the complex current plane. (This is the RF engineer's choice. A second convention, preferred by physicists, puts V_c / Z_e on the real axis). Evidently the *voltage* V_c cannot be represented in a *current plane* but, since Z_e is a *real* quantity, the current V_c / Z_e gives the direction of V_c. V_c / Z_c on the other hand, since Z_c is an *imaginary* quantity, must be at an right angle to V_c / Z_e and hence their phasors must meet on a *circle* which has the phasor $2\, I_f - I_b$ as diameter.

The diagram is drawn with an angle φ between the phasors of forward current I_f and beam current I_b. This angle represents the *station phase*. It can be set from the control room. We have also phase angles between the cavity voltage V_c and the beam current I_b and the forward current I_f respectively. The first of these angles is the one which really matters for particle acceleration: It is the *synchronous phase* ϕ of the bunches (measured from the crest of the voltage) and has to be kept at a prescribed value. The second angle (between V_c and I_f) influences the efficiency of power transfer between generator and beam and ideally should be made zero (the transmission line then 'sees' a *real load*) by a proper choice of both station phase and cavity detuning.

2.3 The detuning condition

A formula for the required cavity detuning is readily obtained: In fact, for real values of Z_e, V_c and I_f equ. (2) implies a real I_r, and equ. (3) then also a real value of $V_c/Z_c + I_b$, i.e. V_c/Z_c must compensate the imaginary (quadrature) component of the RF beam current.

$$\frac{V_c}{Z_c} + j I_{bi} = 0 \quad \text{or} \quad \frac{1}{Z_c} = -j\,\frac{I_{bi}}{V_c} \tag{7}$$

and calling the required normalized detuning the *optimal detuning* d_o we get with (5)

$$d_o = -\frac{Z_e}{V_c} I_{bi} = -(R/Q)\, Q_e \frac{|I_b|}{V_c} \sin\phi \quad . \tag{8}$$

The following vector diagram represents an optimally detuned case. Station- and synchronous phase are now equal.

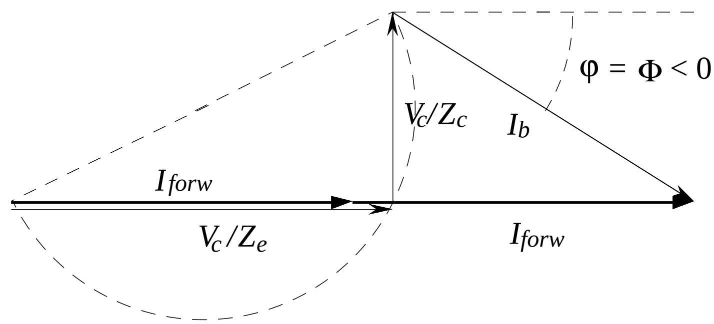

Figure 4: Phasor diagram for optimal detuning

2.4 The matching condition

With a superconducting cavity we may realize a 100% power transfer efficiency to the beam : In addition to detuning we couple such that $V_c/Z_e = I_f$. In fact from equ. (2) then $I_r = V_r = 0$ (no reflected power) or $V_c = V_f$ and from equ. (3) $I_f = I_{br}$ and we may calculate the required external Q of the coupler from the cavity voltage V_c and the in-phase component I_{br} of the RF beam current:

$$Q_e = \frac{Z_e}{R/Q} = \frac{V_f / I_f}{R/Q} = \frac{V_c / I_{br}}{R/Q} \quad . \tag{9a}$$

We may also introduce the matched power which we want to transfer to the beam: With $2P_b = V_c\, I_{br}$:

$$Q_e = \frac{V_c^2}{V_c I_{br}} \frac{1}{R/Q} = \frac{V_c^2}{2P_b} \frac{1}{R/Q} \quad . \tag{9b}$$

As we see from equ. (9a) we match to a given *ratio* of cavity voltage and in-phase beam current.

3 Non matched states

3.1 The general formulas

To start the discussion of non matched states we solve equ. (6) for the cavity voltage V_c and obtain

$$V_c = \frac{2I_f - I_b}{1 + jd} Z_e. \tag{10}$$

Of special interest for the operation of a power coupler is the reflection coefficient $\rho = V_r/V_f$. With $V_c = V_r + V_f$ and $V_f = Z_e I_f$ we find from equ. (10):

$$\rho = \frac{V_c}{Z_e I_f} - 1 = \frac{2 - I_b / I_f}{1 + jd} - 1. \tag{11}$$

3.2 Cavity voltage with optimal detuning

Let us now assume that two cavities, via a power divider, receive identical incident powers P_i and have individual tuning loops which assure detuning to $d = d_o$. We then may substitute equ. (8) into equ. (10) to obtain

$$V_c = Z_e (2 I_f - I_{br}) = 2 V_f - Z_e I_{br} \quad . \tag{12}$$

In addition, a voltage loop which measures the field in the first of the two cavities (cavity a) shall keep its voltage constant at $V_c = V_{ca}$ in acting on the generator to produce the appropriate forward voltage V_{fa}. From (12):

$$V_{fa} = \frac{1}{2}\left(V_{ca} + Z_{ea} I_{br}\right). \tag{13}$$

In general voltage reflection will occur and from $V_{fa} + V_{ra} = V_{ca}$ follows with (12) and (13) :

$$V_{ra} = \frac{1}{2}\left(V_{ca} - Z_{ea} I_{br}\right). \tag{14}$$

Evidently from (14), for our reference cavity the matching in-phase beam current is $I_{bra} = V_{ca} / Z_{ea}$. We proceed in calculating from V_{fa} the incident power Pi which in turn allows to determine both the forward voltage V_f to the second cavity and its voltage V_c :

$$V_c = 2\left(Z_e / Z_{ea}\right)^{0.5} V_{fa} - Z_e I_{br}.$$

Substituting (13) and dividing the beam current by I_{bra} we arrive at

$$\frac{V_c}{V_{ca}} = \sqrt{\frac{Q_e}{Q_{ea}}}\left(1 + \frac{I_{br}}{I_{bra}}\right) - \frac{Q_e}{Q_{ea}} \frac{I_{br}}{I_{bra}}. \tag{15}$$

Note, that as a consequence of equ. (15) for small beam currents ($Ibr < Ibra$) and undercoupling ($Qe > Qea$) the cavity field becomes higher than the nominal one. This is illustrated in the figure below, taking the LEP cavity with its nominal gradient of 6 MV/m as example. The used range of Qe / Qea corresponds to what is found for the present fabrication methods of cavities and couplers.

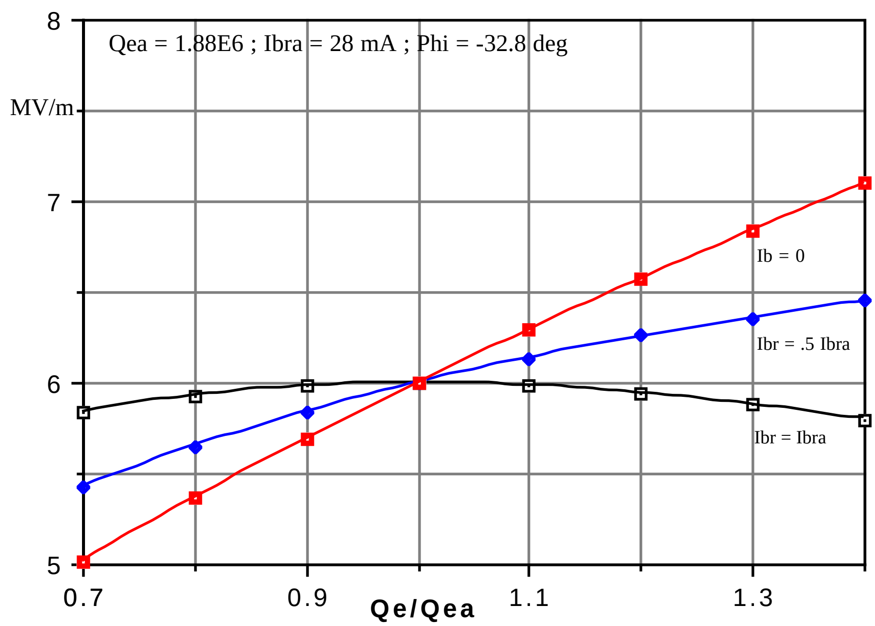

Figure 5: Coupling dependence of the acc. gradient for three different beam currents

3.3 Enhanced fields in the coupling line

Coupling errors may also enhance the field in the coupling line. We first will regard the coupler of our reference cavity and find that the in-phase beam current I_{br} must not exeed the nominal current I_{bra}

Introducing in (13) and (14) the matching current $I_{bra} = V_{ca} / Z_{ea}$ and writing $\bar{I} = I_{br} / I_{bra}$ gives

$$2 V_{ra} = V_{ca} - (Z_{ea} I_{bra}) I_{br} / I_{bra} = V_{ca}(1 - \bar{I})$$

and

$$2 V_{fa} = V_{ca} + (Z_{ea} I_{bra}) I_{br} / I_{bra} = V_{ca}(1 + \bar{I})$$

and by division

$$\rho_a = \frac{1 - \bar{I}}{1 + \bar{I}} = 1 - \frac{2\bar{I}}{1 + \bar{I}}. \tag{16}$$

The maximal voltage on the 'abstract' transmission line is $V_{max} = (1 + |\rho|) V_f$. Here for currents $\bar{I} \le 1$:

$$\left(1 + |\rho_a|\right) V_{fa} = \frac{2}{1 + \bar{I}} V_{fa} = \frac{2}{1 + \bar{I}} \frac{V_{ca}}{2}\left(1 + \bar{I}\right) = V_{ca}. \tag{17}$$

For all currents $\bar{I} \le 1$ the maximal voltage is equal to the travelling wave voltage at the match point. Danger starts only for in-phase beam currents bigger than the matching one.Then $\rho < 0$ and

$$\left(1+|\rho_a|\right) V_{fa} = \frac{2\bar{I}}{1+\bar{I}} V_{fa} = V_{ca}\bar{I} .$$

It is therefore mandatory, if no construction with variable coupling strength is available, to match for the highest planned beam intensity.

Having done this for the reference cavity of our discussion a second cavity with weaker coupling will reach the match point at a current $I_{br} < I_{bra}$ and at I_{bra} already suffer from field enhancement. Quanti-tatively equations (13) and (14) now can be written ($V_{ca} = Z_{ea} I_{bra}$ is used)

$$2V_r = V_{ca}\left(\frac{V_c}{V_{ca}} - \frac{Z_e}{Z_{ea}}\bar{I}\right)$$

$$2V_f = V_{ca}\left(\frac{V_c}{V_{ca}} + \frac{Z_e}{Z_{ea}}\bar{I}\right)$$

After substitution of equ. (15) and division follows for the second cavity

$$\rho = 1 - \sqrt{\frac{Q_e}{Q_{ea}}\frac{2\bar{I}}{1+\bar{I}}} \quad . \tag{18}$$

Finally, comparing fields in the coupling lines of the two cavities we find that for $Q_e > Q_{ea}$ and $\bar{I} = 1$ field is enhanced by the square root of Q_e/Q_{ea} .

3.4 Tuning offsets

In the accelerator RF language a tuning offset is a deviation from optimal detuning. In LEP a tuning offset is systematically used: Cavities are operated near to their resonance frequency ($f_g \approx f_c$)i.e. the quadrature component of the beam is not compensated.

In fact, due to their construction from thin walled metal sheets sc cavities are much more sensitive to mechanical perturbations then conventional Cu cavities responding even to noisy flow of liquid helium with vibrations at their mechanical eigen-frequencies. These vibrations are translated into phase- and amplitude modulations of the cavity voltage, the more the bigger the detuning and may even, at high voltage and detuning degenerate into self-sustained ‘ponderomotive’ oscillations [3].

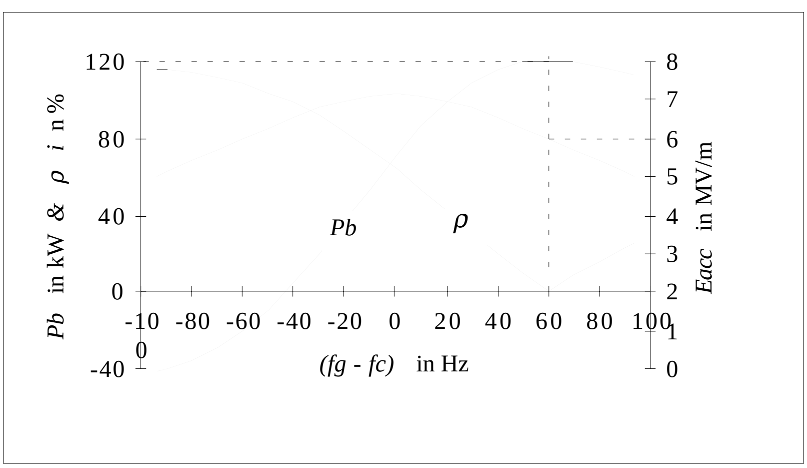

Figure 6: LEP cavity: Detuning from the matched operating point

To illustrate offset effects for LEP the figures 6 and 7 have been prepared, using equations (10) and (11) directly for numerical calculations. Fig. 6 shows the effects of cavity tuning for the nominal dc beam current of 2x7 mA, an incident power of 120 kW, a station phase of -33 deg and $Q_e = 1.9 \; 10^{-6}$: With 7 MV/m the accelerating gradient peaks at $f_c = f_g$ but there the power transmitted to the beam is only 70 KW. With a detuning of $f_g - f_c$ = 60 Hz the reflection becomes zero and the beam power rises to 120 kW at 6 MV/m but we are on the slope of the resonance curve of V_c!

Optimal operating parameters with no detuning *($f_c = fg$)* are used in figure 7: P_i has been increased to 132.5 KW and the station phase decreased to -14.5 deg. Then at zero detuning 120 KW are delivered to the beam at the nominal gradient of 6 MV/m i. e. the synchronous phase angle has its correct value of -33 deg. Calculating from the reflected power of 12.5 KW the module of ρ and then $(1+|\rho|)^2 P_i$ we obtain the traveling wave power equivalent to the maximal voltage in the coupler line. Here we find 226 KW. Up to this power the coupler has now to be free of multipactor discharges in traveling wave operation. And to even higher powers if coupling errors are taken into account.

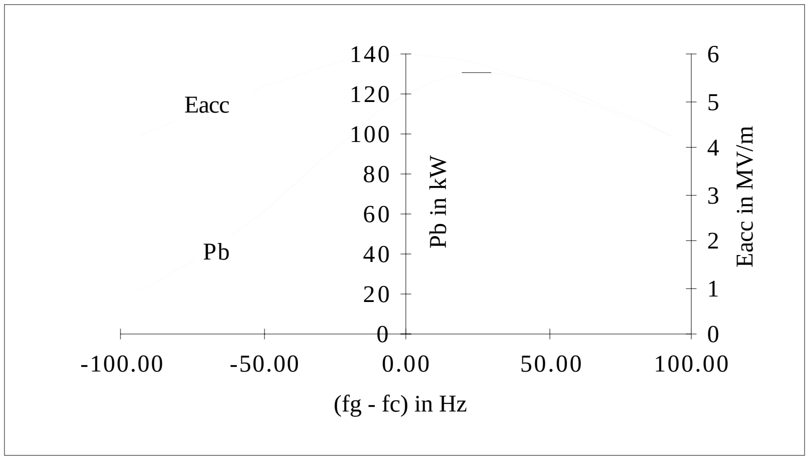

Figure 7: LEP cavity operation with optimal parameters for zero detuning

The original LEP coupler design had a first serious multipacting level at 85 KW. Increasing the wave impedance of the coupling line from 50 Ω to 75 Ω allowed to shift this level to 130 KW. But a break-through improvement was obtained after adding capacitive insulations [4] which allow to polarize the inner conductor of the coupling line with 2.5 KV dc against the outer conductor. More recently, during a test on a single cell sc cavity with both an in- and output power coupler, multipactor free traveling wave operation up to 600 KW has been realized [5].

References

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[5] M. Stirbet, Private Communication.