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Developments of HOM couplers for superconducting cavities

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I. Introduction

Coherent instabilities limit the beam current in circular machines (coupled bunch instabilities) or in linear accelerators (regenerative, cumulative and multipass BBU). These instabilities are mainly caused by the long range wakefields excited by the beam bunches as they passed through the cavities. The best way to increase the threshold is to hasten the decay of the excited fields, in other words to damp the higher order modes of the cavities once the shunt impedances are fixed. Typical Q values under 10^5 or 10^4 for the most dangerous parasitic modes are required in present designs of accelerators.

Various devices and especially designed for superconducting cavities have been developed during the last years. The main differences lie in the type of coupling - hole, probe or loop - and in the way of rejecting the accelerating mode. But all the last versions follow the same rule : they couple through the beam tube and not directly in the cells. The risk of multipacting and also of thermal breakdown is thus avoided. However care must be taken in the design of cavities with the so-called trapped modes, for which though above cut-off, the field goes rapidly to zero outside the cavity.

II. Estimation of the extracted power by HOM couplers

The cavity codes like Superfish [1] or Urmel [2] help in designing couplers that will be mounted on the beam tube. In fact if we know the electromagnetic fields at the location of the coupler and if we assume i) the coupling port does not disturb too much the field pattern and ii) the rf device behaves like an ideal filter without reflection, we can easily deduce an approximative value of the real damping that will be effectively measured on a copper prototype.

For waveguide coupling

The predictions can be hazardous because the theory generally developed concerns only small coupling holes (see for instance [4]). We could use instead 3D cavity codes like MAFIA [3] combined with one of the two later on described methods to evaluate the power flow through the waveguide terminated on a rf load. Otherwise the waveguide coupler and the matching waveguide stubs have to be developed empirically.

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For loop or probe coupling

The estimations deduced from field level calculations with Urmel or Superfish agree very well with the measurements.

For a probe coupler the electric flux arriving on the probe tip furnishes the current induced by a cavity mode :

$$I = \omega \varepsilon S E$$

Where E is the electric field from a mode averaged over probe tip and S is the antenna area. The external Q of this simple coupler terminated on a resistive load R for a mode with stored energy W is

$$Q_{ex} = \frac{2 W}{R \omega \varepsilon^2 S^2 E^2}$$

In the same way for a loop coupler the magnetic flux going through the loop furnishes the voltage induced in the loop by a cavity mode :

$$V = \omega \mu S H$$

Where H is the magnetic field from a mode averaged over the loop and S is the loop area. The external Q of this simple coupler terminated on a resistive load R for a mode with stored energy W is

$$Q_{ex} = \frac{2 R W}{\omega \mu^2 S^2 H^2}$$

For illustration we consider the dipole modes of a 3-cell cavity equipped with one loop coupler on the beam tube. The loop couples to the axial component of the magnetic field and the dipole modes are polarized in the plane of the coupler. The calculated and the measured Qex for the two first passbands are reported in table 1 and are in good agreement.

Frequency (Mhz)	Normalized H	calculated Q (10^4)	measured Q (10^4)
2021	6,4	0,84	0,83
2048	10	0,34	0,35
2103	9	0,41	0,38
2156	6,9	0,68	0,69
2190	4	1,99	2,10
2204	2	7,92	7,50

Table 1 - Calculated and measured Qex of the two first dipole passbands for a 3-cell cavity equipped with a loop coupler.

III. The coupling via beam tube and its limits

The most efficient HOM coupler will be inadequate whenever the field level will be vanishing at the location of the coupling port. Measurements on a single cavity [5] showed the existence of modes above cut-off which couple poorly to the propagating waveguides modes. The situation is even worse in the case of a multicell cavity.as these trapped modes appear at a frequency well below three times the fundamental mode frequency [6].

The cavity codes predict these troublesome modes. For example figure 1 shows the plots of the electrical field of two modes above cut-off for a 5-cell cavity with large iris aperture (ϕ/λ=0.35). One mode (top) belonging to the fifth dipole passband remains confined inside the cavity in contrast with a preceding mode (bottom) which couples clearly to the propagating TE11 mode. We expect for these trapped modes a very poor damping by the HOM couplers but we could hope to evacuate the power by propagating waves through the beam pipes.

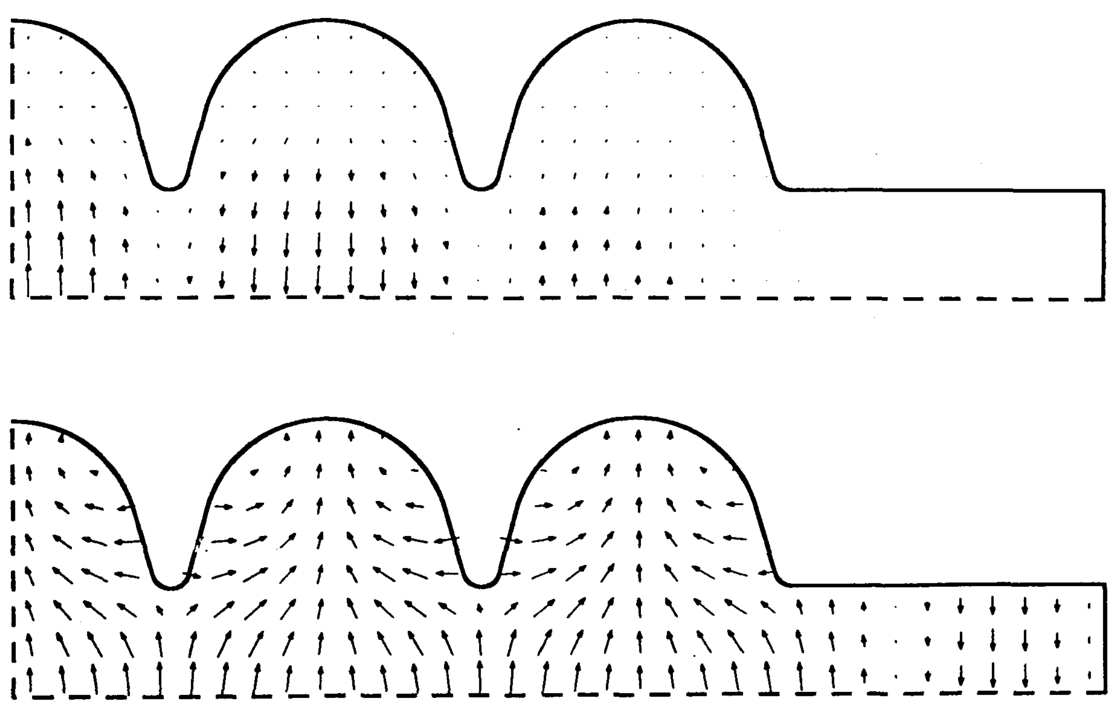

Figure 1 - Plots of the electrical field of two dipole modes above cut-off for a large iris aperure 5-cell cavity.

IV. Estimation of the extracted power by propagating waves

With the help of the cavity codes we can estimate the maximum power flow assuming the cavity isolated from the others with the two beam tubes terminated by perfectly matched resistive loads. As the codes do not allow dissipative boundary conditions the correct power flow can be indirectly deduced with the help of the circuit theory of waveguiding systems. The model used for a cavity mode above cut-off coupling with a propagating wave in the beam tube is a parallel LC resonator connected to a transmission line with length L and wave impedance Z_c. On figure 2, to is the " plane of detuned short " of the cavity (almost coincides with the plane of the outer iris) and t1 is the plane of the load. A dipole mode couples mainly to the dominant TE11 wave of the circular guide and the beam tube length is choosen long enough for the evanescent modes to be completely vanished. A first method [7] uses the equivalent voltage/current values when the waveguide is terminated by an open/short circuit. A second method known as "pulling effect by reactive loading" uses the frequency shifts with different beam tube lengths.

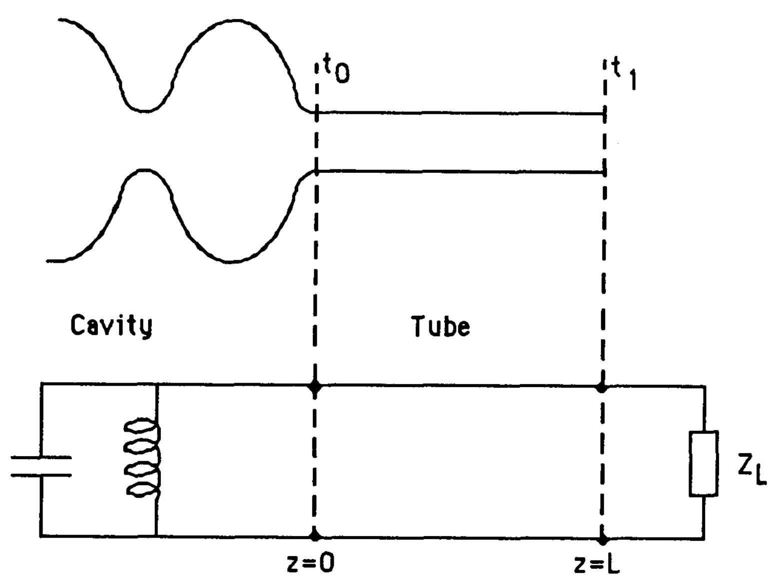

Figure 2 - Model used for a cavity and its beam tube.

Results for a reduced iris aperture 3-cell cavity

We applied the two methods to the less coupled mode of the fifth dipole passband for a 3-cell cavity with small iris aperture (ϕ/λ=0.25). The formulae which were used for calculating the damping with all the available power dissipated in a matched load are given in annex. Table 2 gives the normalised field magnitudes calculated by Urmel and the deduced external Q with the voltage-current method for different tube lengths. We note the very good reproductibility and a Q value of 3900 is expected. Figure 3 points out the frequency shifts due to reactive loading against different short-circuited (electric boundary) waveguide lengths. The theoretical curve fits very well the data with a Q value of 4100 in agreement with the first method. The region where the two branches of the curve are diverging corresponds to resonances of the waveguide which occur when the tube length is a multiple of half the guide wavelength.

L tube cm	10	12	14	16	18
F (short) Mhz	3586,82	3586,10	3585,77	3585,15	3587,72
Ha (short)	2,80	1,36	1,33	2,52	5,08
Ea (open)	2,90	6,50	7,55	2,99	2,68
Q ex	3915	3913	3902	3911	3911

Table 2 - Calculated Qex with the voltage-current method of the less coupled dipole mode for a small iris 3-cell cavity.

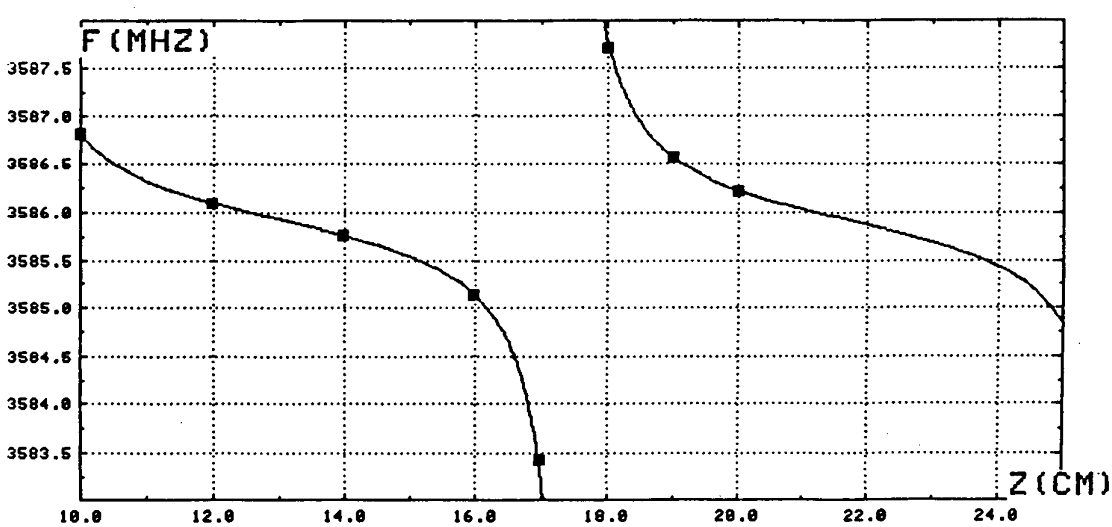

Figure 3 - Frequency shifts due to reactive loading against short-circuited waveguide length.

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Results for a large iris aperture multicell cavity

In the same way the lowest external Q's via beam tube we can hope were estimated for the less coupled modes of the fifth dipole passband for a large iris aperture multicell cavity (ϕ/λ=0.35) with varying the number of cells. The results are showed on figure 4. The Qex value rises to 10^5 for a 3-cell, $3 10^5$ for a 4-cell and $7 10^5$ for a 5-cell cavity. We note that the damping is about two orders of magnitude weaker compared to the precedent small iris aperture 3-cell cavity.

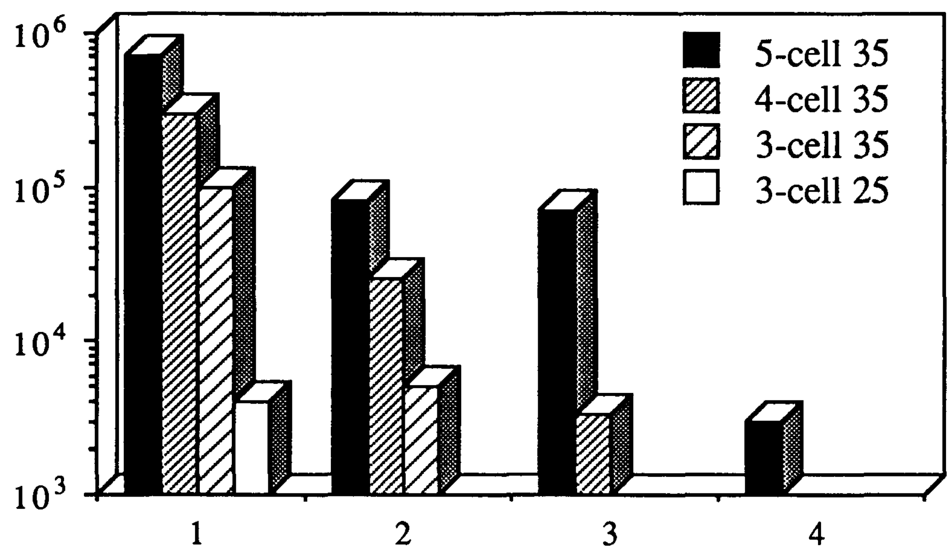

Figure 4 - Calculated Qex of the less coupled modes in the 5th passband for different iris diameters and number of cells.

All these calculations enable to assess the extent of the trapped modes in different structures but assume ideal boundary conditions which can not be easily predicted in a real configuration. On the other hand a real HOM coupler couples hardly more than 10% of the maximal available power. Fortunatly the less coupled modes have low R/Q and we have to compare the product R/Q times Q for structures with different number of cells and iris hole diameters. From this point of view the optimal structure could be between a 4-cell cavity where the modes are not very well damped but have very low R/Q and a 3-cell cavity where the modes are well better damped but have higher R/Q.

Table 3 reports the measured Qex for a copper 5-cell cavity equipped with antenna couplers (shunt impedance in ohm/m^3).The fifth passband is very poorly damped in agreement with measurements made at DESY [8]. For comparison Table 4 shows the measured Qex for the most dangerous dipole modes on a copper 3-cell cavity equipped with loop couplers. We find again the more classical situation where the most dangerous deflecting modes belong to the two first dipole passbands (TM110 or TE111-like modes).

Freq (Ghz)	Passband	Z"/Q (10^4)	Q (10^4)	Z" (10^8)
3,46	#5	0,9	2200,0	1980
3,45	#5	0,2	5400,0	1080
3,48	#5	0,6	500,0	300
2,14	#2 (TM110)	12,0	5,8	70
2,16	#2 (TM110)	3,4	10,3	35
3,39	#4	5,7	4,5	26
3,05	#3	9,2	2,7	25
2,85	#3	13,9	1,7	24
2,09	#2 (TM110)	9,4	2,2	21
3,41	#4	2,1	9,2	19
1,86	#1 (TE111)	13,6	0,6	8
1,94	#1 (TE111)	14,6	0,5	7

Table 3 - Measured Qex of the most dangerous dipole modes for a large iris aperture 5-cell cavity.

Freq (Ghz)	Passband	Z"/Q (10^4)	Q (10^4)	Z" (10^8)
2,18	#2 (TM110)	23,0	1,5	35
2,20	#2 (TM110)	6,6	4,7	31
2,03	#1 (TE111)	18,3	1,6	29
3,03	#3	66,3	0,3	20
2,15	#2 (TM110)	11,5	1,1	13
2,09	#1 (TE111)	19,0	0,6	11
2,00	#1 (TE111)	1,1	3,3	4
3,52	#5	1,0	3,0	3

Table 4 - Measured Qex of the most dangerous dipole modes for a small iris aperture 3-cell cavity.

V. What is required of a HOM coupler

The rf requirements

In addition to the damping of all dangerous modes as much as needed we require of a HOM coupler that the coupling with the fundamental mode must be kept as small as possible. In the case of the waveguide coupler this requirement is naturally fulfilled with appropriate cut-off frequency and length. However because of the large size and rectangular shape of waveguides, coaxial couplers combined with a SC filter for suppression of the fundamental mode are preferred for low frequencies. On the other hand care must be taken on the tuning of the filter which has to be precise enough to reach external Q better than 10^{11} and on the cooling of the inner parts to avoid excessive heating and quench. In the range of a few gigahertz both types have been developed in different laboratories.

The "engineering" requirements

Besides the rf properties of the couplers the laboratories try hard to simplify the design and reduce the cost as much as possible. However the HOM coupler designer has to face often conflicting "engineering" requirements :

- **Low cost**

- **Effective Cooling** of the SC parts exposed to high fields for preventing from thermal quench

- **Compact structure and minimal size** to fit in the cryostat

- **Dismountability** allows surface treatments or thin film deposition of the cavity alone

- **Avoidance of any rf windows in contact with helium** to suppress the damages to the cavity in case of vacuum failure

The salient features of the various existing couplers are reviewed below and schematic drawings of the couplers scaled to 1. GHz can be seen on figure 6.

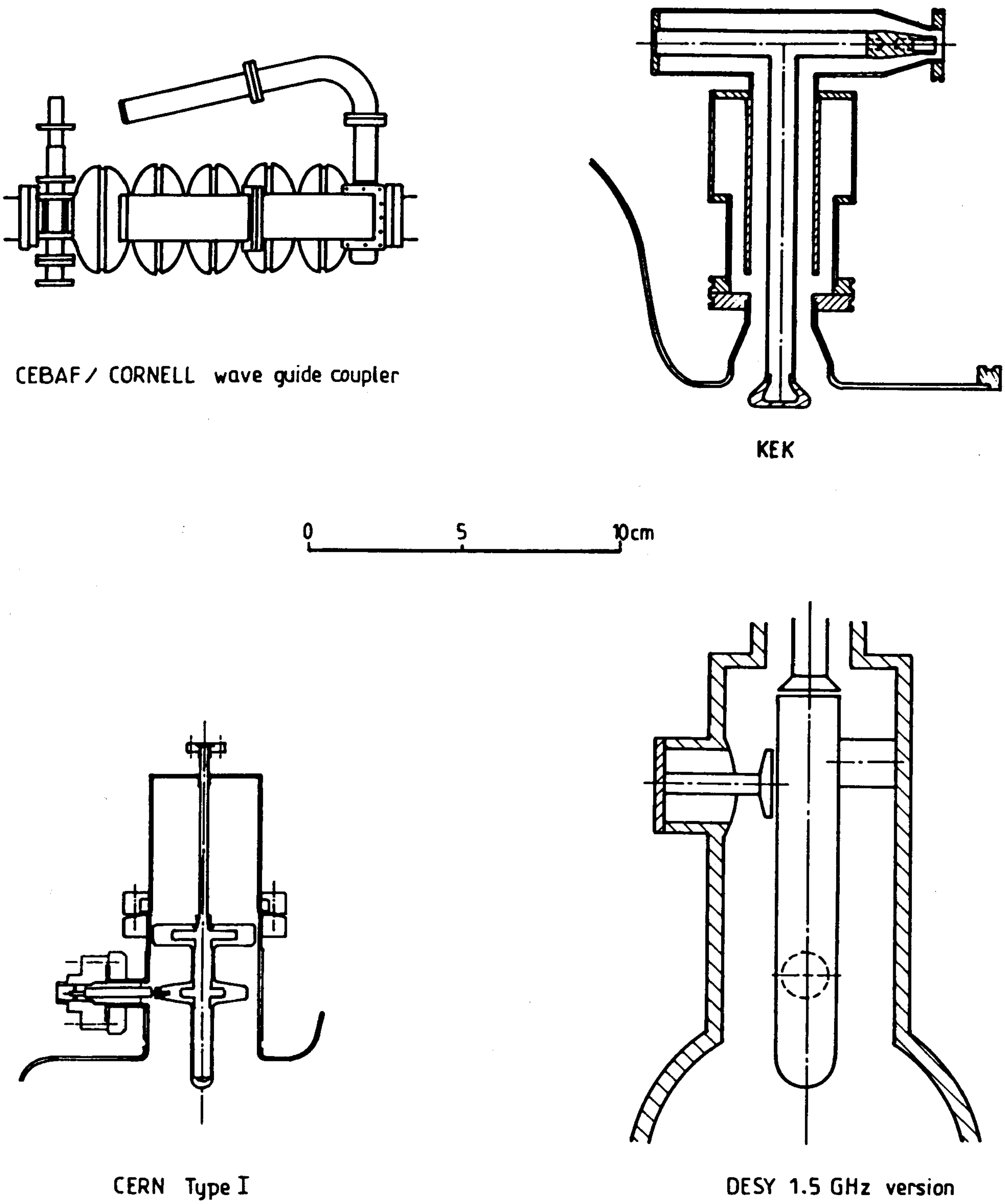

Figure 6 - HOM couplers scaled at 1. GHz (except the Cornell waveguide coupler).

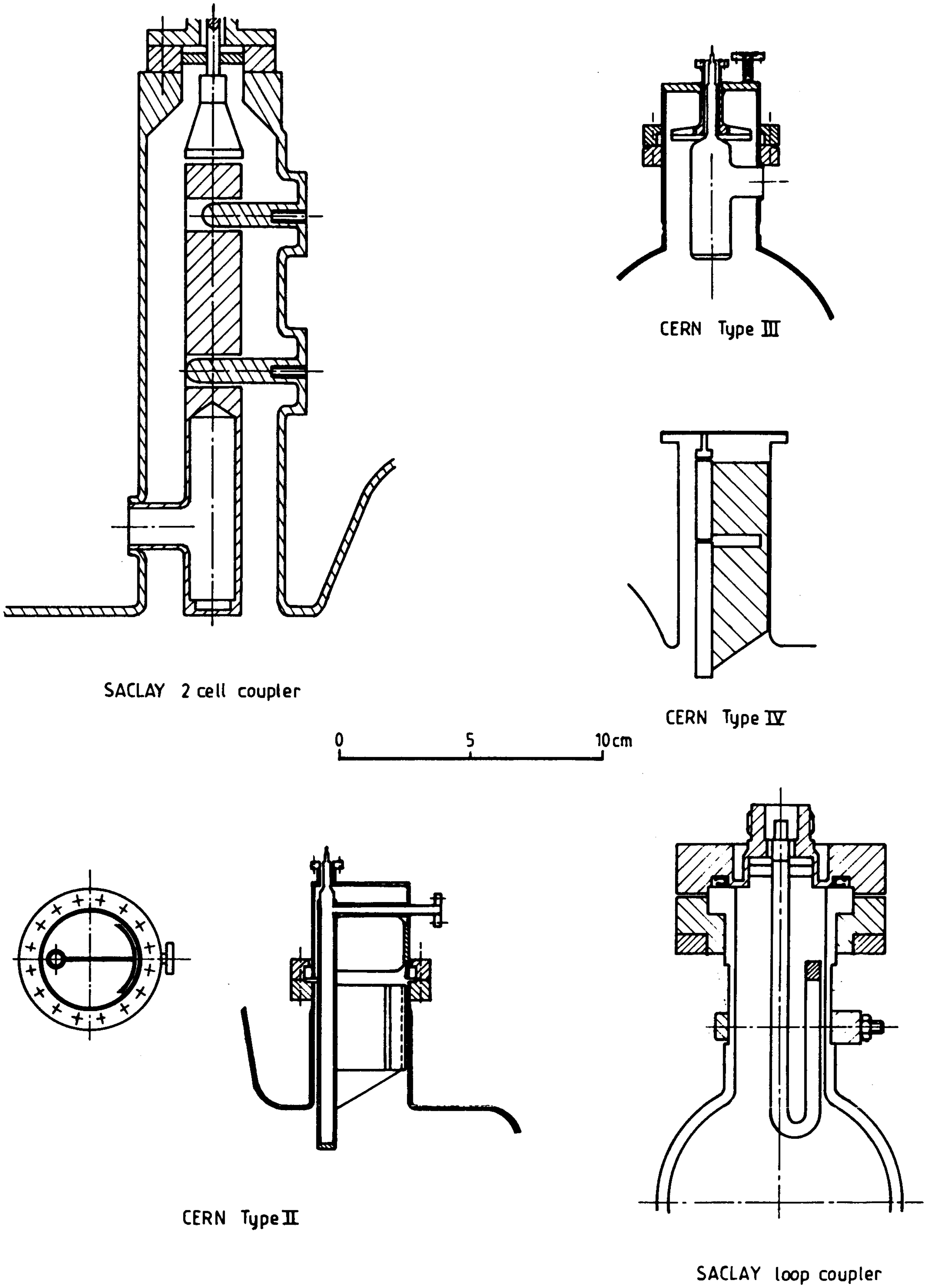

Figure 6 (continued)- HOM couplers scaled at 1. GHz .

VI. Waveguide couplers developments

The main advantage of the waveguide coupler is its high pass feature without the need of any tuning. The evanescent wave in the guide excited by the accelerating mode of the cavity must be sufficiently attenuated before arriving to the rf load. However a guide length of a few wavelengths is needed because the cut-off frequency is generally very near from the fundamental mode. The first waveguide flange has to be far enough from the beam tube for a negligible dissipated power. In addition a matching stub is required on the beam tube at the opposite side of the HOM coupler.

In the CEBAF/Cornell cavity [9] as the cut-off frequency is slightly higher than the first HOM's frequency, the fundamental coupler plus one extra stub is used for their extraction. In order to avoid a pinning of the dipole mode polarizations by the main coupler, the Y configuration (two arms for extraction and one arm as matching stub) for the HOM couplers was adopted.

Further improvements at Cornell [10] allowed to couple out the lowest frequency modes through a modified coupling port of the HOM coupler and hence to eliminate the large stub on the fundamental power coupler.

VII. Coaxial couplers developments

For designing HOM couplers one needs first to choose the way of suppressing the fundamental mode and then to manage the rf elements to produce a broadband transmitter for damping properly the HOM's. For an antenna or loop coupling one must compensate the stray capacitance between probe tip and cavity walls or the self inductance of the loop. Numerical methods are used to optimise the rf circuit before the final adjustment by measuring the transmission curve of a coupler prototype. For illustration figure 5 shows the measured and the calculated response curves for the type I Saclay coupler.

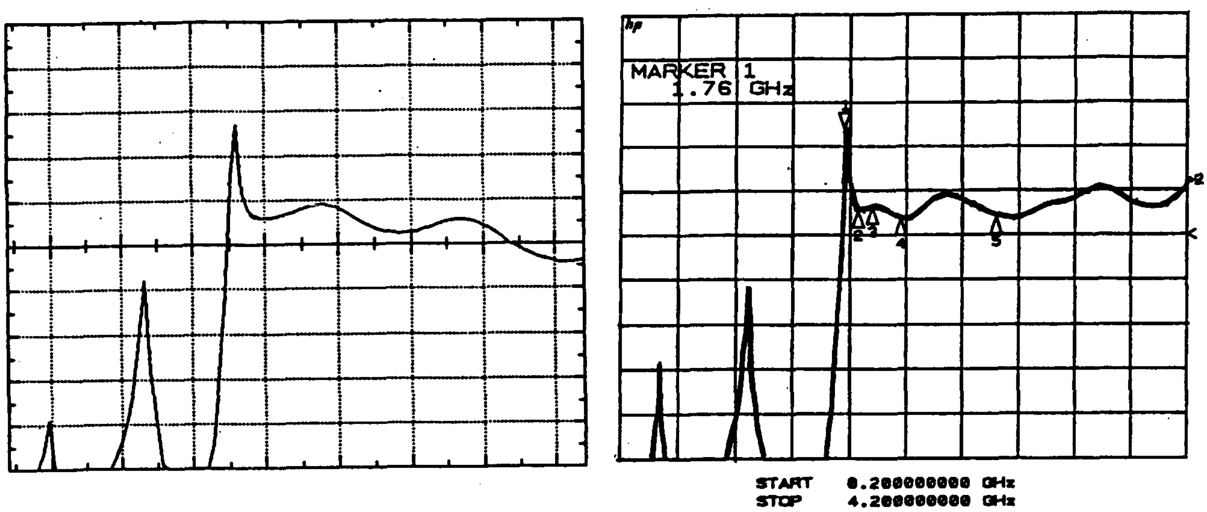

Figure 5 - Calculated (left) and measured (right) transmission curves of the Saclay two-cell filter HOM coupler.

We may distinguish in the present designs3 families in the way of rejecting the fundamental mode and are summarized in table 5. When a lumped element filter is used, the stopband is carried through a simple LC resonator : either a series LC resonator parallel to the load or a parallel LC resonator in series with the load. In the last case the filter has not to support the large reactive current of the fundamental mode but is a little more complex to realize. While a distributed element filter behaves like a waveguide with a cut off frequency.

1- The series LC resonator

The first of this type is the CERN Type I coupler [12]. It is fully dismountable but requires 3 small sapphire rods for a precise centering within the coupling port.

The addition of self inductances between the inner and outer conductors and before the filter bypasses the low frequency waves and reduces the current through the resonator. These hollow posts allow also easy cooling of the inner parts.

The couplers developed at DESY for the 500 Mhz HERA cavities uses 2 inductive posts which are welded to the cavity walls [13]. Last cold tests with full material instead of Nb tubes for the posts showed that cooling by only thermal conduction is sufficient at least up to 5 MV/m [14]. On the other hand further developments demonstrated the feasibility of a rescaled and simplified version of the coupler at the higher 1.5 Ghz frequency [8].

At Saclay the first type developed for a 1.5 Ghz cavity uses a single post and a two-cell filter which exhibits a very large stopband (about 10 times more). This configuration enables to reach high external Q without severe mechanical tolerances [6] but leads to a little too cumbersome structure. The Saclay Type II loop coupler belongs also to this family and will be described in detail in next chapter.

2- The parallel LC resonator

A capacitively loaded $\lambda/4$ resonator on the outer conductor is the most elegant way of forming a such filter. As the current is zero in front of it, a flange allows to dismount the filter.

The CERN Type III coupler is very compact but the single post supporting the inner conductor and used for cooling is welded to the cavity [12].

The KEK coupler is fully dismountable and includes a T stub at the exit allowing the cooling of the inner conductor. As other notches at higher frequencies two couplers with shifted higher notch frequencies are mounted on a beam tube [11]. Multipactor occurs at a low level of field but disappears after half an hour [15].

3- The distributed element filter

This family is derived from the lunar guide which has a cut-off frequency like a waveguide. To shorten the needed length for a sufficient attenuation either a distributed condenser along the sheet close by the outer conductor (CERN Type II) or a local LC resonator formed by a little aperture in the lunar guide (CERN Type IV) has been added [12]. While the second is welded to the cavity walls the first is fully dismountable but with a filter only cooled by heat conduction with the risk of thermal quench.

series LC		parallel LC	distributed
without post	*with posts*		
CERN I ** SACLAY II **	DESY SACLAY I	CERN III* KEK **	CERN II** CERN IV

Table 5 - List of coaxial HOM couplers classified according to the type of the rejection filter (the asterisks mean partially* and fully** dismountable couplers).

VIII. Cost savings by reduction of the number of coupling ports and HOM couplers

Any reduction of the number of coupling ports and HOM couplers lower obviously unit costs. The degeneracy of each deflecting mode of a real cavity into a pair of polarized modes requires generally the use of two HOM couplers. If there was only one coupler the two polarizations would be fixed by the coupler itself leading to an inadequate damping of one polarization. In order to reduce the number of coupling ports the first idea is to use the fundamental power coupler as a HOM damper and to mount a single HOM coupler in another plane. This imposes however severe constraints on the design of the power coupler which needs now to be broadband. The second idea proposed at Cornell [10] is to shape azimuthaly the cavity (12 chords joined by circular arcs) so that the polarization of the deflecting modes is fixed by the wall perturbation and not by the single coupler. RF measurements on a 5-cell copper cavity and cold tests on Nb polarized cavities showed the validity of the method and the absence of any multipactor.

IX. Last developments at Saclay

After the development of the two-cell filter coupler for the 1.5 Ghz 5-cell cavity the study of a much simpler coupler (Saclay type II) was justified for a cavity with lower number of cells which presents not only a much lower sensitivity to the multicell trapped modes but also improved features for the accelerating mode. The basic idea is that a loop normal to the beam tube axis couple very strongly to the dipole modes and not to the azimuthal magnetic field of the fundamental TM010 mode. As a loop couples not only to the H but also to the E-field the monopoles modes are also to a less extent damped but a stopband filter had to be added to suppress the current induced by the electric field of the fundamental mode. The simplest way is to use the natural self inductance of the coupling mechanism and instead of connecting directly the end of the loop to the cavity wall the loop is bended back in face of the outer conductor thus forming the condenser of a LC series filter. For the 1.5 GHz developed coupler the stopband width is indeed about 20 MHz at the needed 40 dB attenuation that is to say 10 times narrower than the 2-cell filter coupler. For a high frequency coupler the severe tolerances can however be removed by a final tuning outside the cavity at room temperature.

Damping measurements have been performed on a copper 3-cell cavity and the results for the dipole modes are listed on table 4. We checked that the monopole modes were also damped and the Qex varies between 10^4 and a few 10^5 for the passbands under cut-off.

For simplicity reasons this special Nb loop was mounted on a standard feedthrough. In this first version the loop is cooled only by thermal conduction without any helium inside but with the risk of forward thermal quench. During a first test on a Nb 3-cell 1.5 Ghz cavity at 2.2°K (a superfluid leak prevented from cooling down to 1.8°K) the measured Qex of the coupler was about $4 10^{12}$ and no thermal quench occured up at least to 6 MV/m. This field was limited by input coupler mismatch and electron loading. Figure 7 shows a view of the 3-cell cavity and the both loop couplers before the cold tests. It is clear that for a lower frequency cavity the longer Nb loop demands He internal cooling at the expense of more complexity. Such a loop coupler scaled to 350 MHz is under development at CERN where great care is taken to a more effective cooling [16].

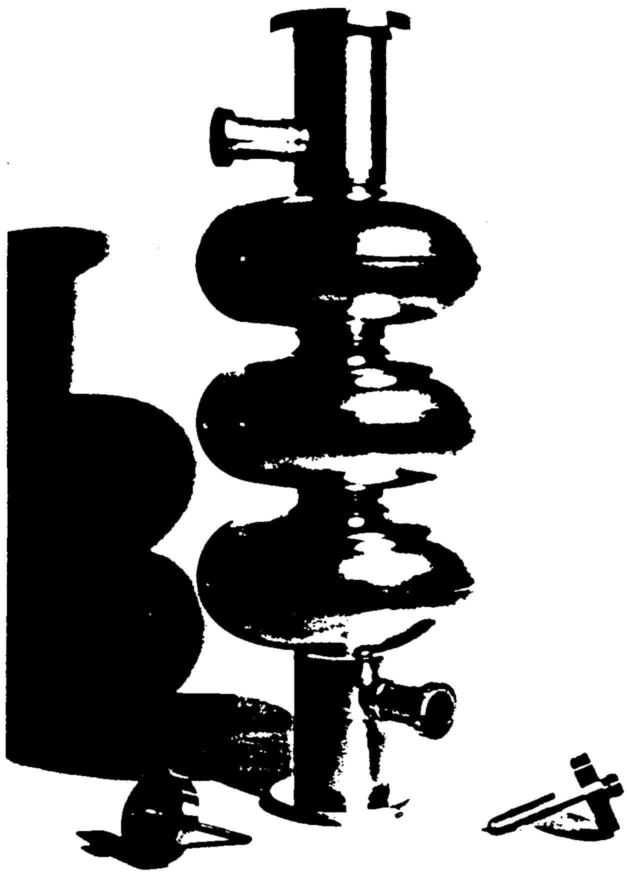

Figure 7 - View of the 3-cell cavity and the both loop couplers.

Annex

The model used for a above cut-off cavity mode propagating in the beam tube is a parallel LC resonator connected to a transmission line with a wave impedance Z_c :

for a TM wave $Z_c = Zo\, \beta / k$

for a TE wave $Z_c = Zo\, k / \beta$

β is the propagation constant in the guide

k is the wavenumber

If we know the open circuit voltage (radial electric field E_r at the beam radius for a magnetic boundary condition) and the short circuit current (azimuthal magnetic field H_ϕ at the beam radius for an electric boundary condition) at the end of the line we can deduce the power P_L that would be dissipated in a matched load ($Z_L = Z_c$).

For a dipole cavity mode which couple mainly to the TE11 waveguide mode the external Q is given by :

$$Q_{ex} = \frac{\omega\ W}{P_L} = \frac{2}{a^2\ (p'_{11}{}^2 - 1)\ \lambda\ (\lambda/\lambda_g)} \left(\frac{1}{E_a{}^2} + \frac{(\lambda/\lambda_g)^2}{H_a{}^2} \right)$$

where W is the energy stored in the cavity

E_a and H_a are the normalised fields :

$E_a = \sqrt{\varepsilon_0/2W}\ E_r$ $\qquad$ $H_a = \sqrt{\mu_0/2W}\ H_\phi$

p'_{11}=1.841 for the TE11 mode of the circular guide

λ is the mode wavelength

λ_g is the guide wavelength

λ_c is the cut-off wavelength

with the following relations $\frac{1}{\lambda_g{}^2} = \frac{1}{\lambda^2} - \frac{1}{\lambda_c{}^2}$ and $\lambda_c = \frac{2\pi\ a}{p'_{11}}$

If we calculate now the frequency shift caused by the reactive loading we find easily for the short circuit case :

$$Q_{ex} = \frac{Z_{c0}\ /\ Z_c}{(\omega/\omega_0 - \omega_0/\omega)\ \tan \beta d}$$

where ω_0 is the eigenfrequency of the resonator

Z_c is the wave impedance at frequency ω : $Z_c = Z_0\, \lambda_g/\lambda$

β is the propation constant : $\beta = \frac{2\pi}{\lambda_g}$

d is the distance between the end of the short circuited line and the "plane of detuned short" of the cavity.

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