BEAM TUBE COUPLERS FOR THE SUPERCONDUCTING LEP CAVITY

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1. INTRODUCTION

The discussions of this session focus on RF superconductivity in LEP. Therefore, I will concentrate on couplers and related RF components for LEP cavities. Thus, my principal subject will be work done here at CERN. Other work will only by mentioned if close enough to our approach and therefore relevant to us.

2. GENERAL CONSIDERATIONS

Which LEP parameters influence directly the coupler design?

2.1 Frequency

First we have to mention the LEP RF frequency of 350 MHz. It is too low to use waveguide couplers as designed for instance in Cornell and Desy [1-2].

Such couplers would be at 350 MHz simply too big to exploit their power capability and would not be compatible with the requirements of cryogenics. The rectangular cross section of standard guide types also poses considerable problems of dimensional stability and tightness of flanges in a vacuum environment.

2.2 DC beam current

The second parameter of influence is the beam current and the way of its concentration into bunches. Machine physicists expect a total beam current of 6 mA DC. Then, a 4-cell cavity, operated at an acceleration gradient of 5 MV/m, will transfer a power of $P_b = V_{acc} \cdot I_b \cdot \sin\theta = 36$ kW to the beam.

As a pratical upper limit of power a maximal RF power of 1 MW will be available per group of 16 cavities. This results in 60 kW per cavity and power coupler and gives a good margin for a possible increase of beam current.

At 5 MV/m and with a cavity R/Q of 464 Ω the stored energy will be

$$U = \frac{V_{acc}^2}{\omega\ R/Q} = 72\ \mathrm{J}\ .$$

To couple the beam power P_b with zero reflection into the cavity, the coupler must have an external Q of

$$Q_{ex} = \omega \frac{U}{P_b} = 4.4.10^6 ,$$

at $P_b = 36$ kW (cavity losses neglected). We assume a power generator with ideal source matching which can be readily obtained in mounting an isolator between klystron and cavities. Q_{ex} then also determines the 3 dB bandwidth

$$\Delta f = f/Q_{ex} = 80\ \mathrm{Hz}\ .$$

We are aware that this bandwidth is much smaller than one got used to from normal conducting systems.

Therefore, in anticipation of possible problems P. Marchand studied in close contact with B. Zotter Robinson damping with high Q cavities [3]. A measurement of resonance frequency fluctuations of the first 4-cell cavity to be produced is being prepared. If fluctuations turn out to be a problem, the cavity might be equipped with a tuner fast enough to eliminate them in a feedback arrangement driven by the phase of the cavity oscillations (fig. 1).

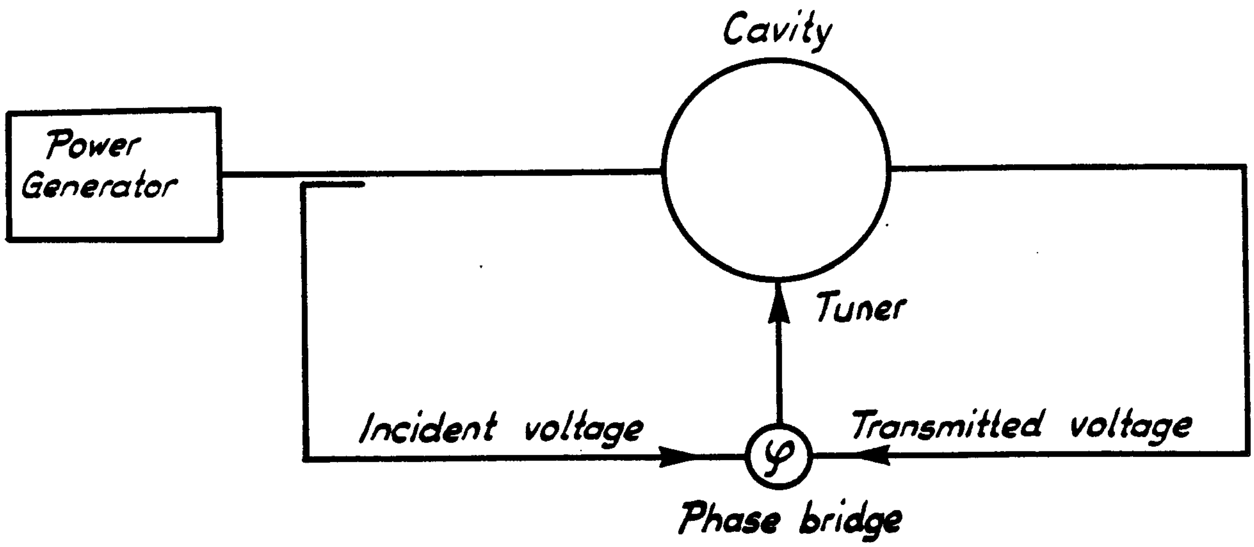

Fig. 1

In our 500 MHz Petra experiment such a scheme has been used to full satisfaction [4]. The cavity had then an external Q of 5.10^5. Tuning was obtained by mechanically deforming the cavity with a setting precision of 50 Hz and a tuning speed of 500 Hz/s. As has been tested more recently in CERN [5], hydraulic motors using supercritical He as working fluid are an elegant way of producing the quite considerable deformation forces and to achieve the tuning range of ~ 20 kHz for operation in LEP.

A "brute force" method to increase the bandwidth would be to couple the cavity tighter as required for a match at 36 kW. If total use of the available 60 kW would be made then 24 kW could be reflected. Hence,

$$\rho = \sqrt{\frac{24}{60}} = 0.63$$

compared to the matched case the source resistance seen by the cavity and so its Q_{ex} is now by the VSWR smaller.

$$Q_{ex\ unmatched} = Q_{ex\ matched}/VSWR\ ,$$

here

$$VSWR = \frac{1+\rho}{1-\rho} = 4.44\ ,$$

and thus

$$Q_{ex\ unmatched} \sim 10^6 .$$

2.3 Beam current structure

The beam current of LEP (4 bunches) seen by the cavities has the form of very sharp pulses with 22.5 μs repetition time. Around the RF frequency its spectrum is comb-like with a line spacing of 44.4 kHz and a line intensity of two times the DC beam current. The small cavity bandwidth at 350 MHz filters out only one line and hence fundamental beam loading is like from a harmonic current source (this justifies the earlier used simple formula for calculating P_b).

On the other hand, for the Higher Order Modes (HOM), it would be ideal, if the cavity voltage could decay between bunch passages. The cavity has then no memory which suppresses multipassage beam instability effects; and the HOM power dissipation into cavity and external load resistors reaches its lower limit [6]. The voltage decay time is

$$\tau = 2\ Q/\omega\ .$$

With the bunch repetition time T_s we need then a HOM external Q of

$$Q_{ex} < \frac{T_s}{2} \cdot \omega\ ,$$

and one needs for the TM_{011} zero mode at 635 MHz which has with 108 Ω the highest computed R/Q of all HOM [7]:

$$Q_{ex} < 45\ 000\ .$$

For the other longitudinal HOM, all with substantially smaller R/Q, we considerer the above criterium too hard and introduce tentatively a correction by the R/Q ratio

$$Q_{ex} < \frac{108}{R/Q} \cdot \frac{T_s}{2} \cdot \omega\ .$$

An inspection of all computed HOM data then reveals, that HOM coupler design has essentially to deal with two longitudinal modes, TM_{011} and TM_{012}, the latter at 1 GHz and requiring an external Q < 250 000.

Adding in also the transverse modes, one can at this point qualitatively say that HOM couplers must begin to provide damping at 455 MHz (TE_{111} frequency), be efficient around 650 MHz (TM_{011} and TM_{111} modes) and continue to work well at least up to 1 GHz.

The beam spectrum reaches up far higher, but there modes are no longer confined to the 4-cell cavities. Therefore, on the beam tube in between cavities, coupling holes shall be equipped with special high frequency couplers, if necessary.

3. THE COUPLING PROBLEM

I want to discuss the coupling problem from the point of view of cavity damping i.e. the emission of energy from a resonator exited to a certain level of stored energy U. We define damping as the reciprocal of external Q

$$\eta = \frac{P}{\omega U} ;$$

P is the emitted power normally absorbed in a load resistor outside of the cryostat.

A very simple way of coupling to the electric field within the beam tube is sketched in fig. 2.

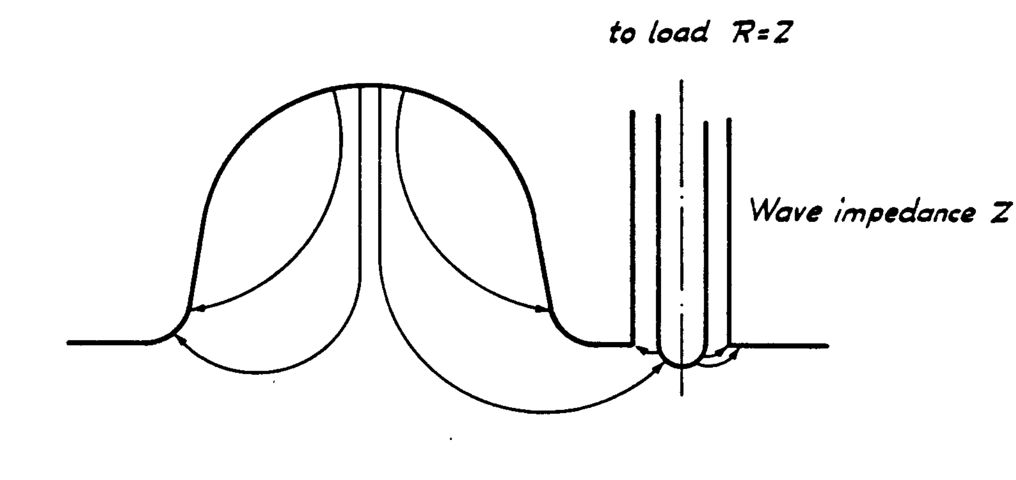

Fig. 2

A coaxial line of wave impedance Z is run down to the beam tube, ending there in an "open circuit". Having then a close look on the electric field lines which emerge from the probe tip, one will find that only part of them belong to the resonator field, the others ending in the direct neighbourhood of the tip.

In an equivalent circuit description of this coupling arrangement, these latter fieldlines correspond to a stray capacitance C_s (fig. 3). A small coupling condenser C_c describes the coupled part of the resonator field and a parallel L and C circuit represent the resonator itself.

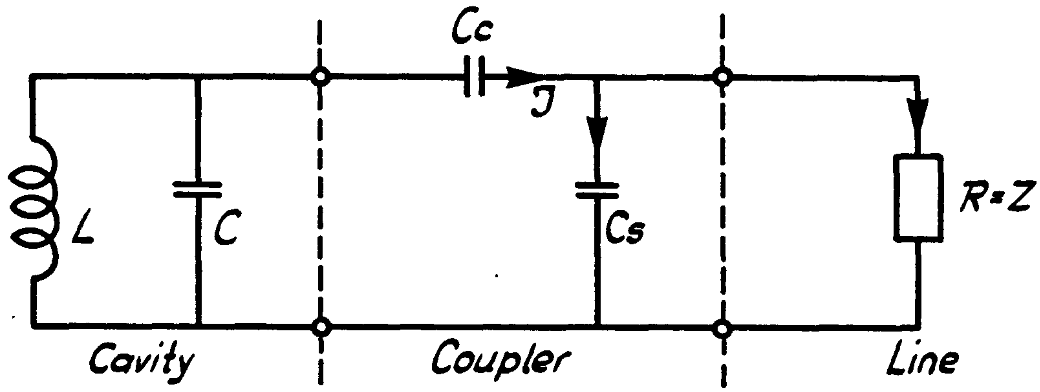

Fig. 3

For the relatively small coupling ($\eta << 1$), which we envisage here, the reactance of C_c is much higher than the impedance of R and C_s in parallel and therefore the current I through C_c (it is the displacement current carried by the mode field lines which arrive at the probe tip) is practically independent of R and C_s.

Consequently, as a first-order simplification, L-C resonator and coupling condenser can be replaced by a current source I (fig. 4).

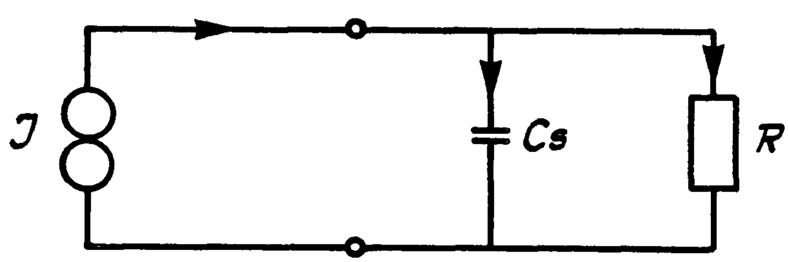

Fig. 4

In a further step of generalization, we can now consider the frequency of the current source as variable and characterize the coupler's broadband damping action by the power dissipated in R. In fig. 4, due to be presence of C_s, this power decreases with frequency. In constructing an electric field coupler, thus any unnecessary stray capacitance must be avoided. Certainly, in connecting an inductance in parallel to C_s (fig. 5) its effect can be exactly compensated at a given frequency f_c and approximately within a certain bandwidth Δf.

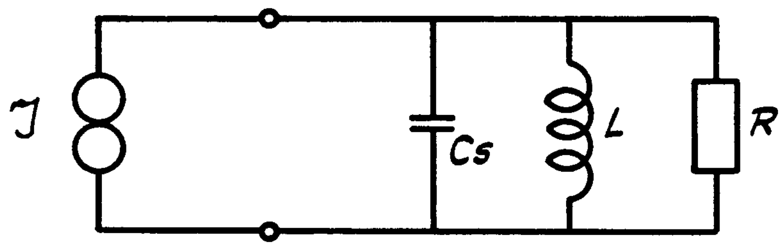

Fig. 5

But now, Δf becomes inversely proportional to RC_s

$$\Delta f \approx \frac{1}{RC_s}$$

and again the smallest possible C_s is desirable.

Another important aspect becomes visible if one imagines R to be variable. The damping effect at f_c is proportional to R. But high R means small Δf. A coupler with given probe geometry has a constant damping-bandwidth product. This remains true also for more complex compensation schemes.

The compensation scheme of fig. 6 describes the HOM E field coupler of the Petra experiment.

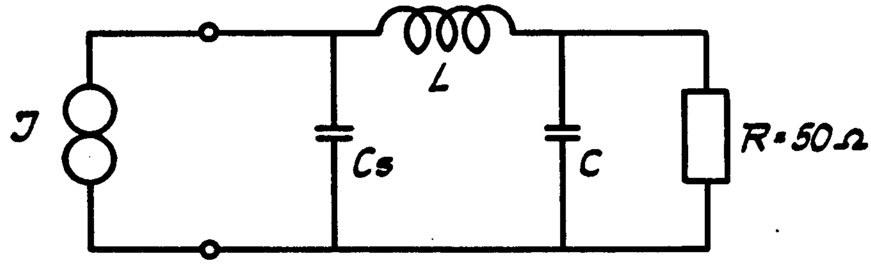

Fig. 6

This circuit allows an up transformation of the 50 Ω load resistance. The transformation can be chosen by C which then also determines the bandwidth Δf. For Petra, the compensation frequency was 1 GHz (the TM_{011} frequency) and the 3 dB bandwidth 500 MHz [8]. This coupler was realized from line pieces as shown in fig. 7.

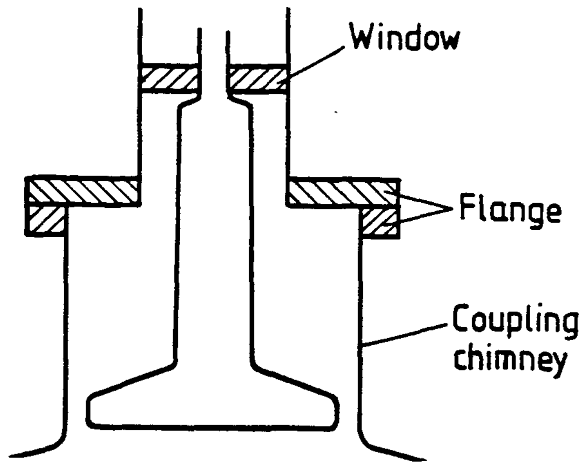

Fig. 7

For cooling purposes, the probe was hollow and filled with liquid He. The A_2O_3 vacuum window capacitance was absorbed into C. Mounted on the cavity equator this coupler performed well. It should especially be noted that no difficulties were encountered with the vacuum windows. But for use on the beam tube further development is necessary, the most important point being to add a fundamental mode suppression filter.

4. THE HOM BEAM TUBE COUPLER

At the first look, two possibilities to supress coupling with the fundamental mode seem to exist: either by a parallel L-C resonator in series with the inductance L or by a series L-C resonator in parallel to the load. Both circuits may provide zero damping on the fundamental mode frequency, but the first one has a damping pole closely below the frequency of zero damping, and the closer to it the smaller the stray capacitance C_s. This makes its filter action very sensible to mechanical tolerances and leaves only the second possiblity for practical applications. Its equivalent circuit is given in fig. 8.

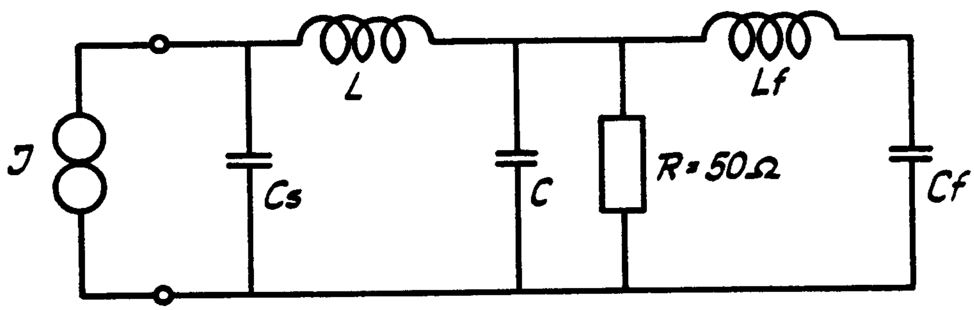

Fig. 8

To determine suitable element values for this circuit we used the fact that at high frequencies, where C_f can be neglected, the circuit is that of a transforming band pass filter whose elements can be calculated analytically. We then continued by systematic "cut and try" on a computer, calculating the power dissipation in the 50 Ω load, first for the equivalent circuit and then for a more realistic model made up of lumped elements and transmission line sections (fig. 9).

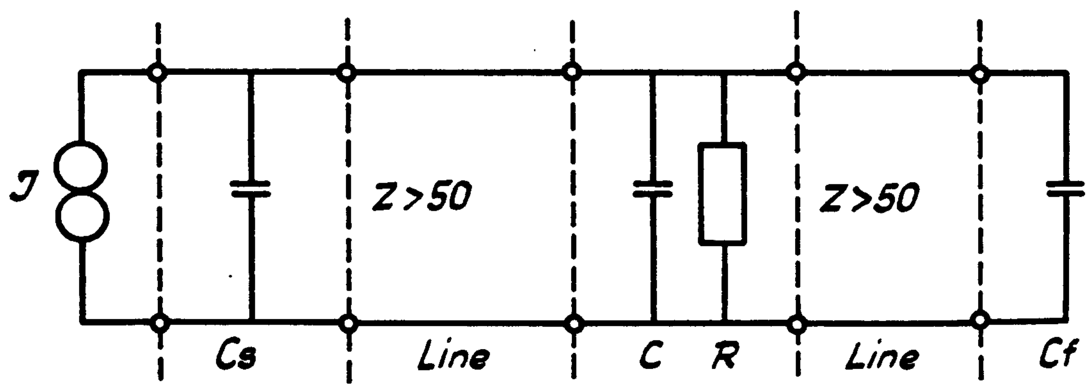

Fig. 9

Calculation results using the finally selected parameter set are given in the figs 10 and 11, which are logarithmic plots of the power dissipation in R versus frequency. Fig. 10 gives an enlarged view on the notch region around 350 MHz.

We see that within a bandwidth of ~ 15 MHz or 4%, a fundamental mode suppression of at least 50 dB is obtained. This is obtained for a filter of infinite Q. On a logarithmic scale, the notch is then

infinitely deep. Finite filter Q leads to finite depth and smaller bandwidth at a given suppression level. The comfortable bandwidth of 15 MHz will allow a mechanical construction without difficult tolerance problems.

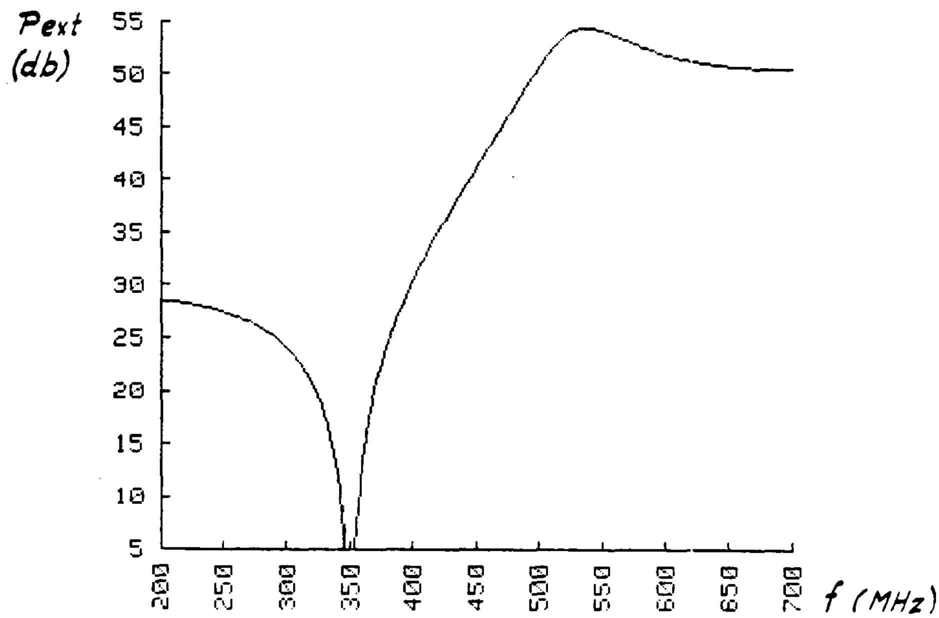

Fig. 10

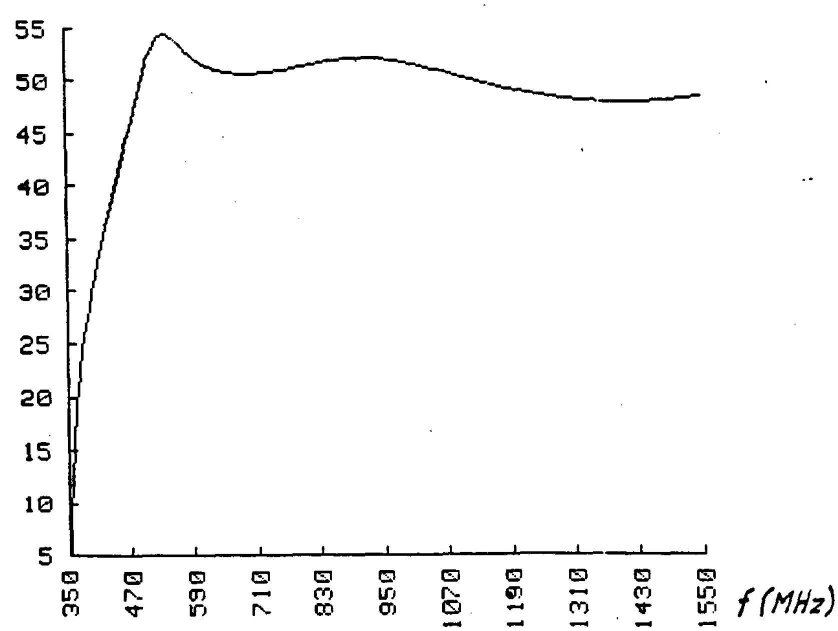

Fig. 11

At this stage of simulation and given the difficulty to estimate stray capacitances accurately, it is appropriate to switch over to hardware constructions. This is our present activity and fig. 12 sketches the geometry of a coupler model which just gave first measuring results. Also the method to check its broadband behaviour is indicated: the coupler is mounted on a section of cut off tube and the transmission between a very short electric antenna near to its probe tip and the coupler's output is measured. We use a tracking generator, spectrum analyser system and obtained the curve of fig. 13 which in fact reproduces the features of the computed power versus frequency curve.

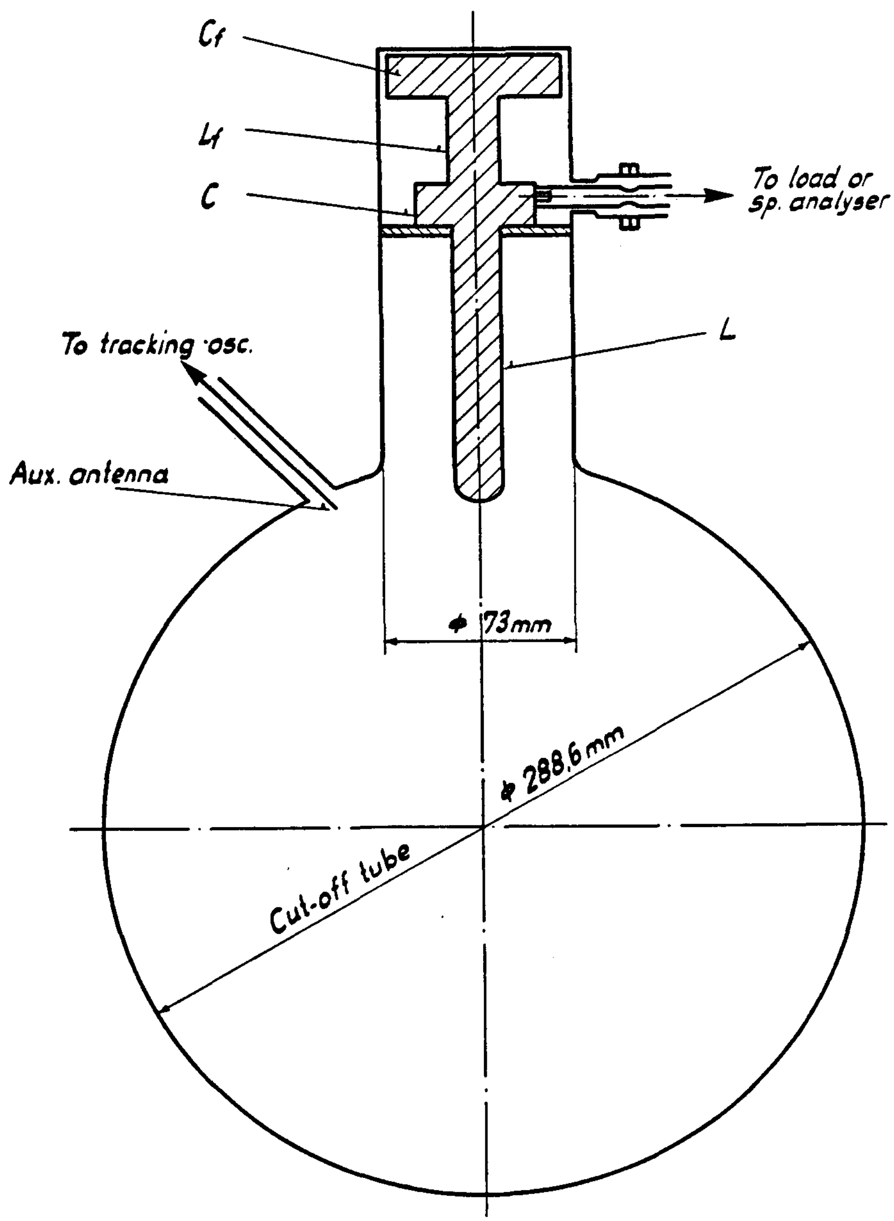

Fig. 12

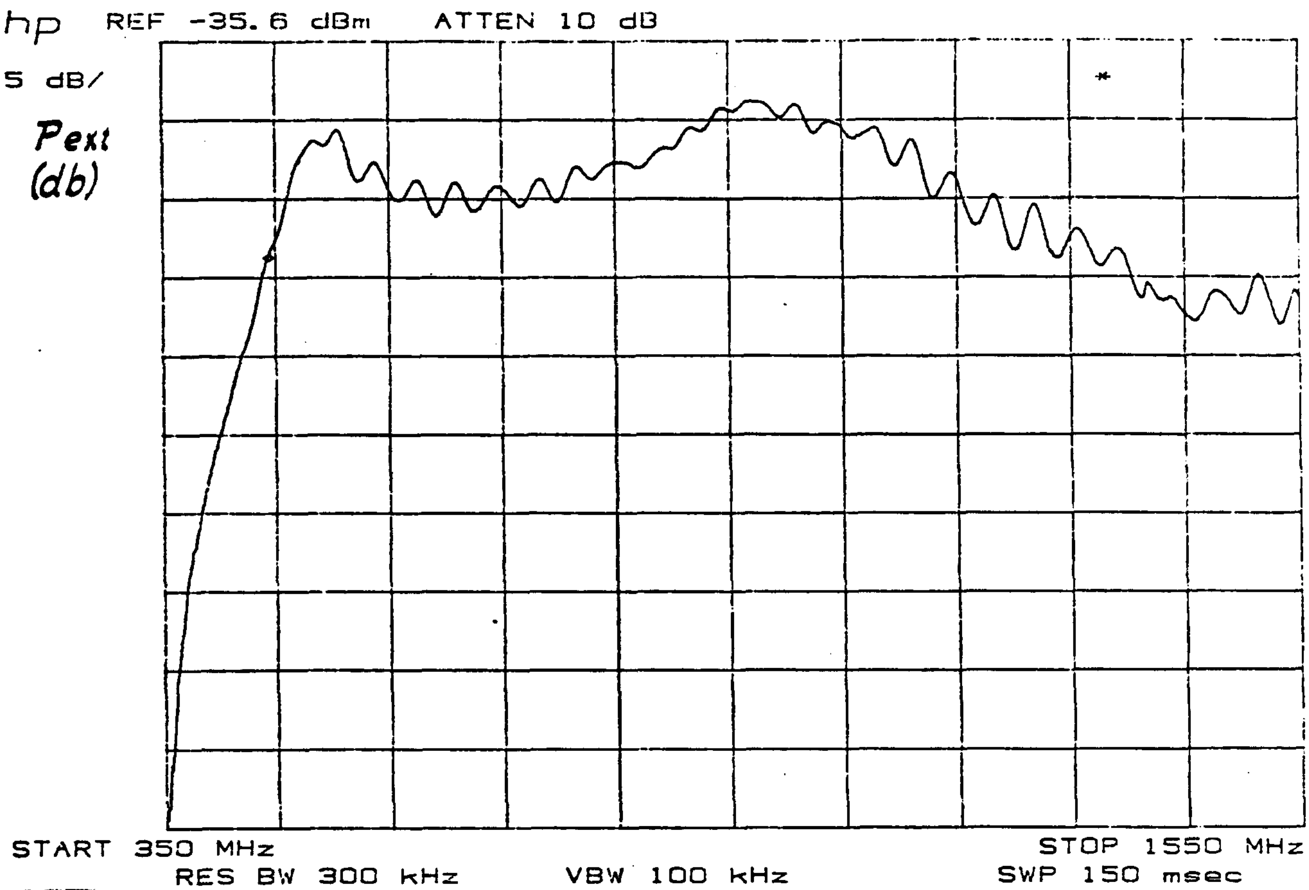

Fig. 13

But the crucial test of a coupler model is certainly to measure its damping action on a cavity. Table 1 gives results obtained recently from measuring the damping of a 4-cell copper cavity prototype equipped with two model couplers, each on one side and at 32° from the horizontal (the coupler has a diameter of 72 mm and its axis is at 45 mm from the weld between end cells and cut off tube; this leaves 8 mm between the coupler outer wall and the weld).

The R/Q values of the table are calculated ones. The definition $R/Q = V_{acc}^2/\omega U$ was used. For dipole modes V_{acc} is the 50 mm off axis value. So far, modes with $R/Q > 2\ \Omega$ have been measured and entered into the table. The results in the fourth column show that all modes of this group are comfortably within the damping region where resonant build-up of harmful fields is prevented.

TABLE 1

f (MHz)	Mode	R/Q(Ω)	Q_{ex}	$\omega T_b/2$
461.93	TE_{111}	8.3	12 000	33 000
476.51	"	7.2	9 000	34 000
496.35	TM_{110}	2.1	8 000	35 000
506.10	"	11.0	10 000	36 000
513.60	"	7.4	11 000	36 000
636.41	TM_{011}	45.8	11 000	45 000
639.23	"	108.0	20 000	45 000
688.55	TM_{111}	25.6	25 000	49 000
996.8	TM_{012}			
1002.6	"	~ 23		71 000
1005.9	"	"	11 000	71 000

The broadband HOM coupler characteristic as measured up to 1550 MHz allows to expect that also modes beyond the TM_{012} will be effectively coupled. In approaching 1550 MHz (the upper frequency limit of the used equipment) the damping curve has a tendency to rise again. Therefore, a computer simulation to higher frequencies has been made. The result is given in fig. 14 and predicts around 2 GHz even more efficient damping than in the range presented here.

A measurement of the fundamental mode current in the coupler's filter has been made on the copper model. Its extrapolated result indicates that at a cavity gradient of 5 MV/m a displacement current of 250 A will be injected into the probe tip. This corresponds to 65 G at the surface of the filter inductor and 6500 V across the gap of the filter condenser. These values are not particularly high, but we feel nevertheless that conductor diameters should be increased.

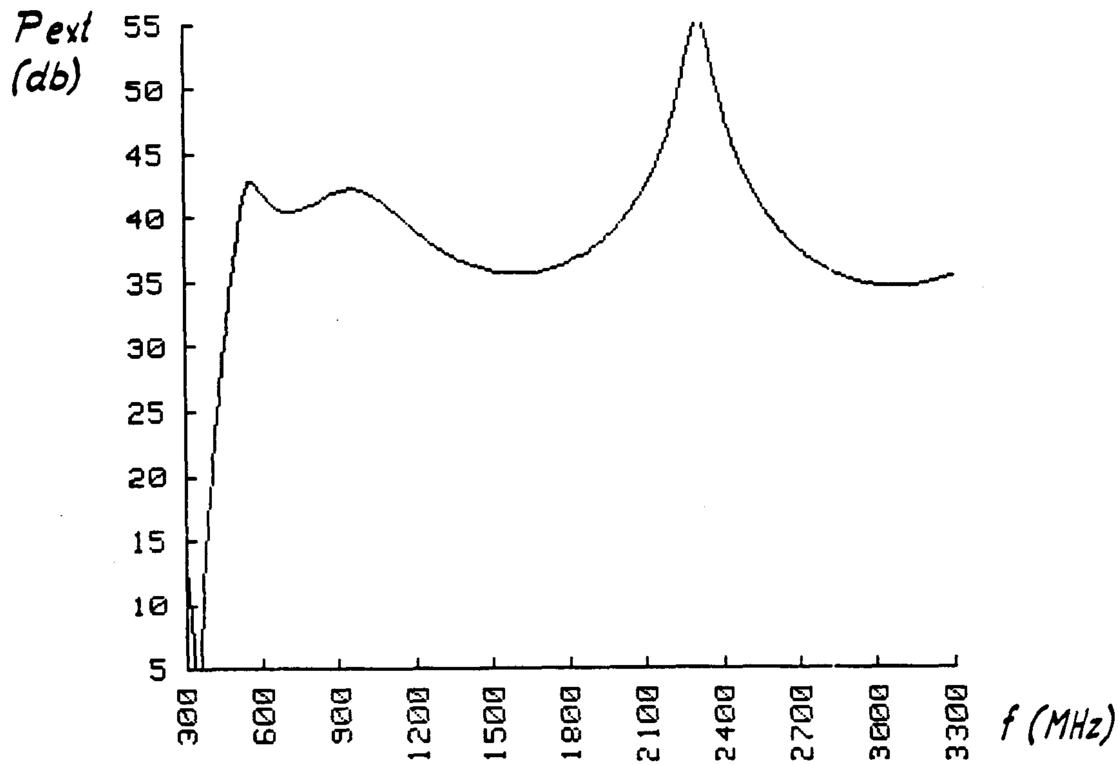

Fig. 14

Fig. 15 shows how a HOM coupler with 10 cm diameter could look. The inner conductor is suspended by a cylindrical, vacuum tight ceramic support, itself attached to a lid which forms part of a Conflat flange system in a field free region of the coupler. Liquid He access to the bore of the central conductor is through this support. There, a tuning screw for the filter frequency could also be mounted.

The HOM power of ∝ 150 W per coupler (at 6 mA beam current) flows sideways via a spring contact, a second, small Conflat flange and a 20 mm diameter vacuum window to the 50 Ω line and load.

5. POWER COUPLER RESULTS AND PLANS

From the point of view of microwave circuit design, the power coupler is a rather dull object. It is a single frequency device and a coupling corresponding to $Q_{ex} \approx 10^6$ is easy to obtain. The simple scheme of fig. 2 is sufficient: a homogeneous 50 Ω line, big enough for the power to be handled, is run down to the beam tube.

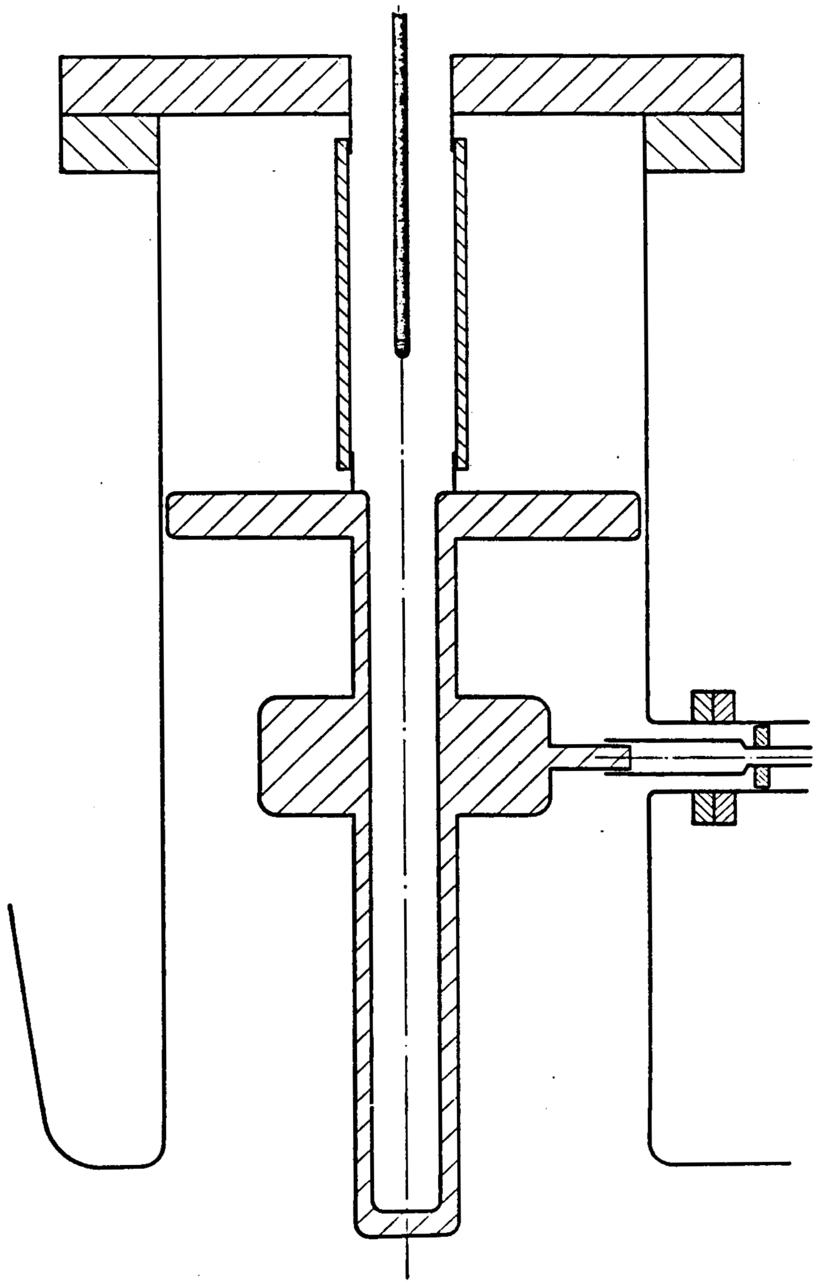

Fig.15

The hidden charm of power coupler design lies in other problem areas; first the question how to bring ~ 50 kW of microwave power down into a 4.2 K environment with minimal heat input into the He bath. One can split up this question further and ask questions about heat produced at cold flanges, at the inevitable transition between superconductor and normal conductors and finally by heat conduction and dissipation on the 50 Ω line.

To take up the last point, it is a good idea to have a look on the rich literature on current leads for superconducting magnets. Here, the method of using cold He gas in countercurrent to the heat flow has been analysed [9]. Computer simulation methods and technical solutions can often be adapted to our needs.

If one asks vacuum specialists to indicate which flange types are reliable elements of construction at 4.2 K and ultra-high vacuum conditions, then the answer is regularly that there is only one, the Conflat flange. But this flange, being made from stainless steel, is a bad RF element. Surely one can find palliatives and I will come back to this later. For the purist however, the situation calls for a choke to keep the RF current away from the flange. Then the flange area also becomes a kind of natural interface between super and normal conducting construction materials. A coupler which has these two ingredients, countercurrent cooling and choke, is the loop power coupler of our Petra experiment [8]. Fig. 16 outlines its geometry. In the coupling area a symmetrical line is used. The power comes down in a standard 3 1/8 coaxial line and a $\lambda/4$ choke provides the transition between balanced and unbalanced line sections. In a warm test facility and using air cooling, we transferred 70 kW to a Cu single-cell cavity. A duty cycle of 10% (100 ms on and 900 ms off) has to be used because air has about ten times smaller cooling efficiency than He gas. During the PETRA test [4] a maximum 20 kW was transferred to the beam. The coupler had to carry this power also under full reflection conditions for extended time periods. With a cooling flow of 0.2 g/s He gas no measurable heat input into liquid He was found. So our experience during operation was that we could "forget" the coupler.

However, there remains a big question mark in this positive picture. The coupler was not long enough in service to test its high power <u>window lifetime</u>. Here is the <u>second big problem area</u> of power coupler construction. Experience has shown that windows often get slowly metallized and increased losses finally break the window, especially if the metallization

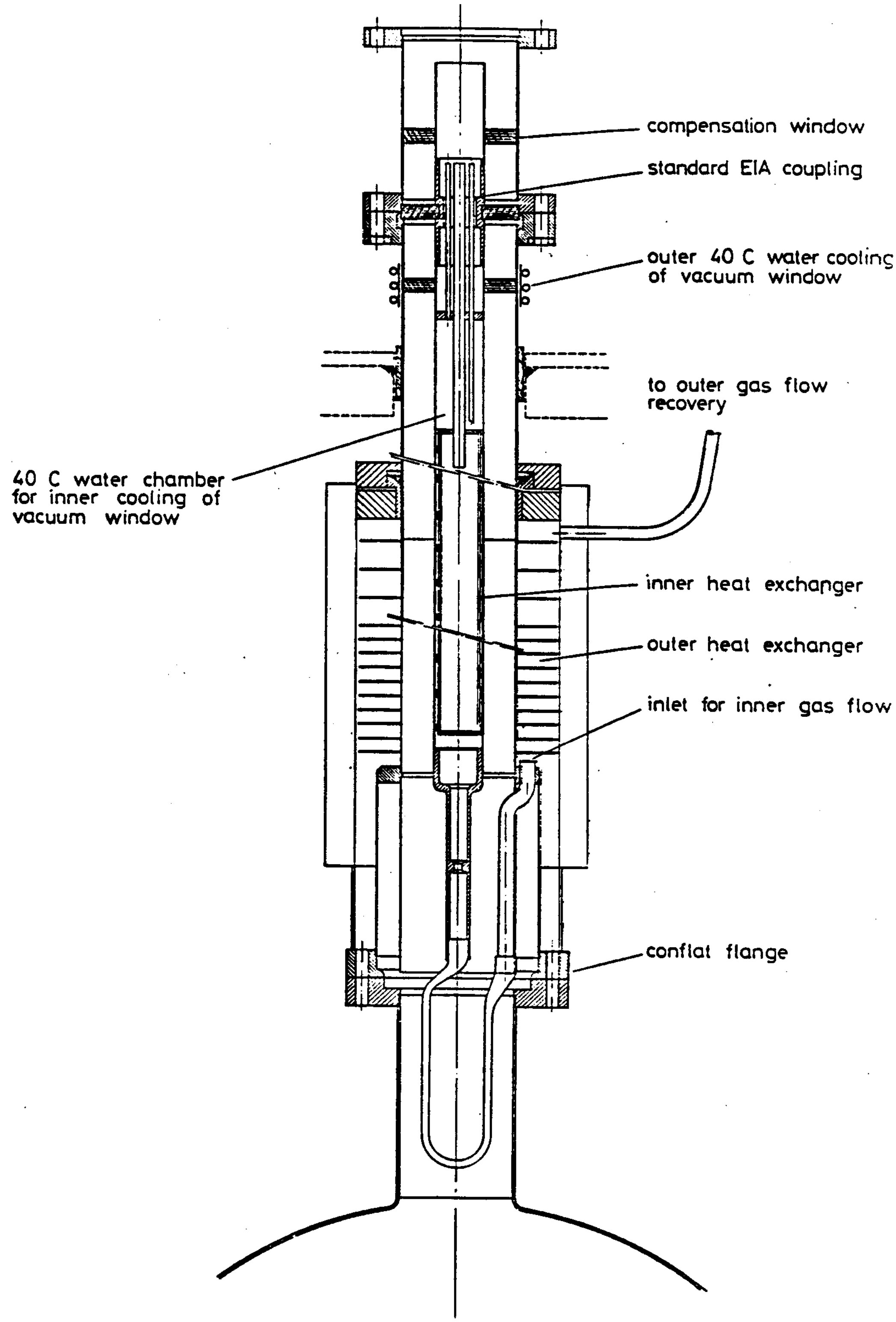
compensation window
standard EIA coupling
outer 40 C water cooling of vacuum window
to outer gas flow recovery
40 C water chamber for inner cooling of vacuum window
inner heat exchanger
outer heat exchanger
inlet for inner gas flow
conflat flange

Fig. 16

is non-uniform. Such a window failure is always a major incident and even more so for a s.c. cavity.

The window is also a possible emitter of contaminants to the cavity. A palliative is to place the window far away from the cavity in order to intercept desorbed gases in the cold parts of the coupler, before they reach the cavity. I believe that the metallization problem requires the window to be placed outside of the cryostat and to be simply demountable. In this respect we are not at all content with our loop coupler design, since in case of window failure the whole unit must be changed.

This brings me to the description of the beam tube power coupler concept presently under study. Its starting point is in fact a well tested window, and a benevolent goddess even allowed us to find it in CERN. It is the window of the warm LEP cavity coupler developed by the group of W. Schnell. Fig. 17 reproduces a shop drawing. It shows a loop coupler with a cylindrical window, integrated into the wave-guide coaxial transition. This coupler will be operated at a 125 kW power level. It has been tested up to 160 kW and ran at high power for ~ 600 h [10]. Note that the central conductor is cooled from the top which allows to remove the bridge between inner and outer conductor without upsetting the cooling. This layout provides us with an antenna type coupler for use on the beam tube.

Fig. 18 gives a recent drawing board study of such a coupler. Antenna cooling is now obtained by cold He gas injected via a transfer line to the bottom of the antenna and recovered around room temperature at the top. Countercurrent cooling is also foreseen for the external conductor. There will be two flanges, a warm one outside the cryostat allowing to change window plus antenna, and for mounting purposes, a cold one at the interface of liquid He and gas. We will try to use here an appropriately prepared Conflat flange (copper plating), but will adopt this simple solution only if tests of heat dissipation give satisfactory results. If not, a version with choke is also possible (fig. 19). Tests of heat input from the power coupler into the He bath shall be made by using a 350 MHz mono-cell cavity, equiped with two couplers, one on each beam tube and

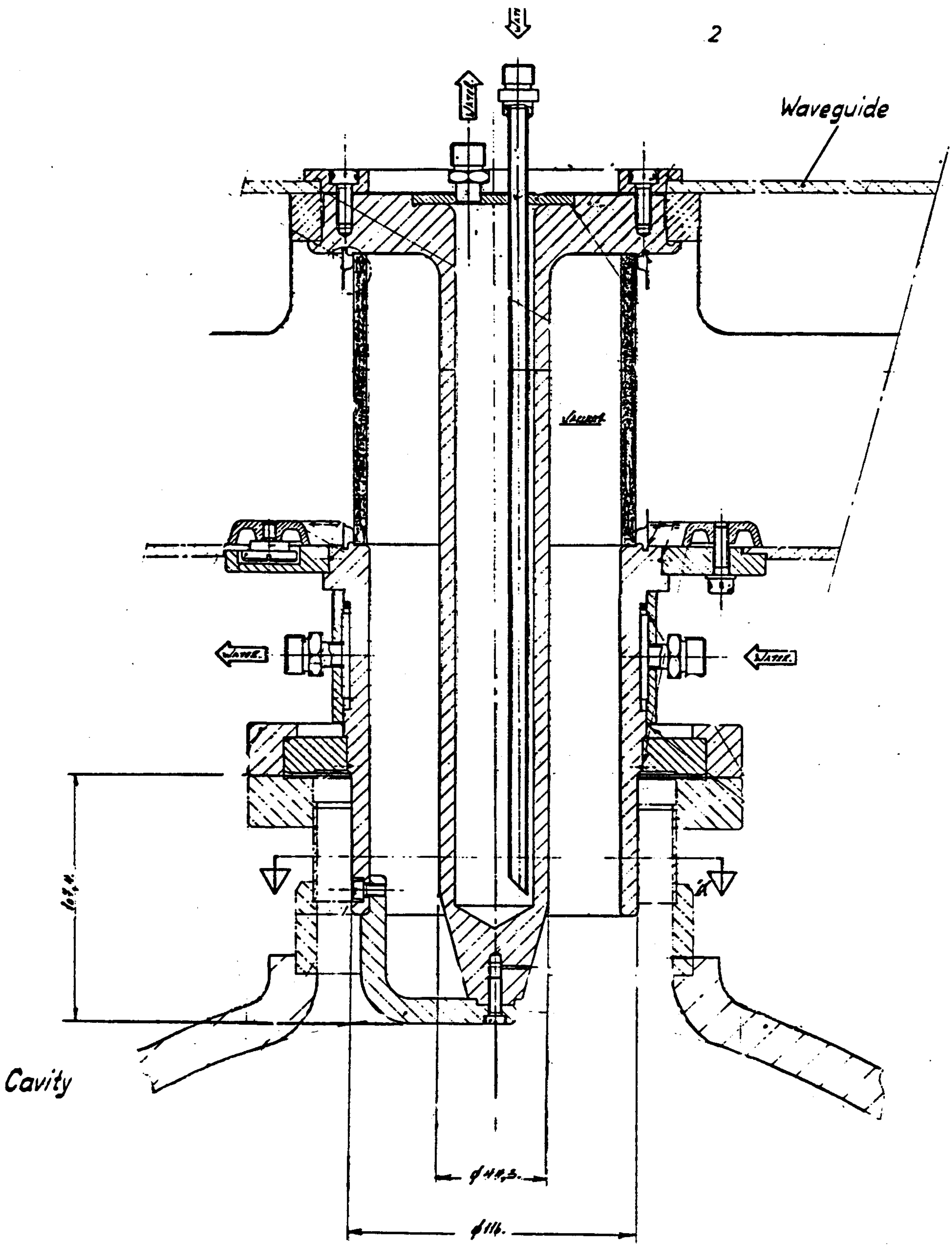

Fig. 17

mounted in a vertical, low loss cryostat (fig. 20). Power shall then be transferred via the first coupler, the cavity and the second coupler to a matched load. With tight coupling, fields in the cavity can be made low enough to make its dissipation negligible and to allow a measurement of coupler losses against the background of cryostat losses. Obviously, final tests will be made at the value of coupling and cavity field foreseen for LEP operation.

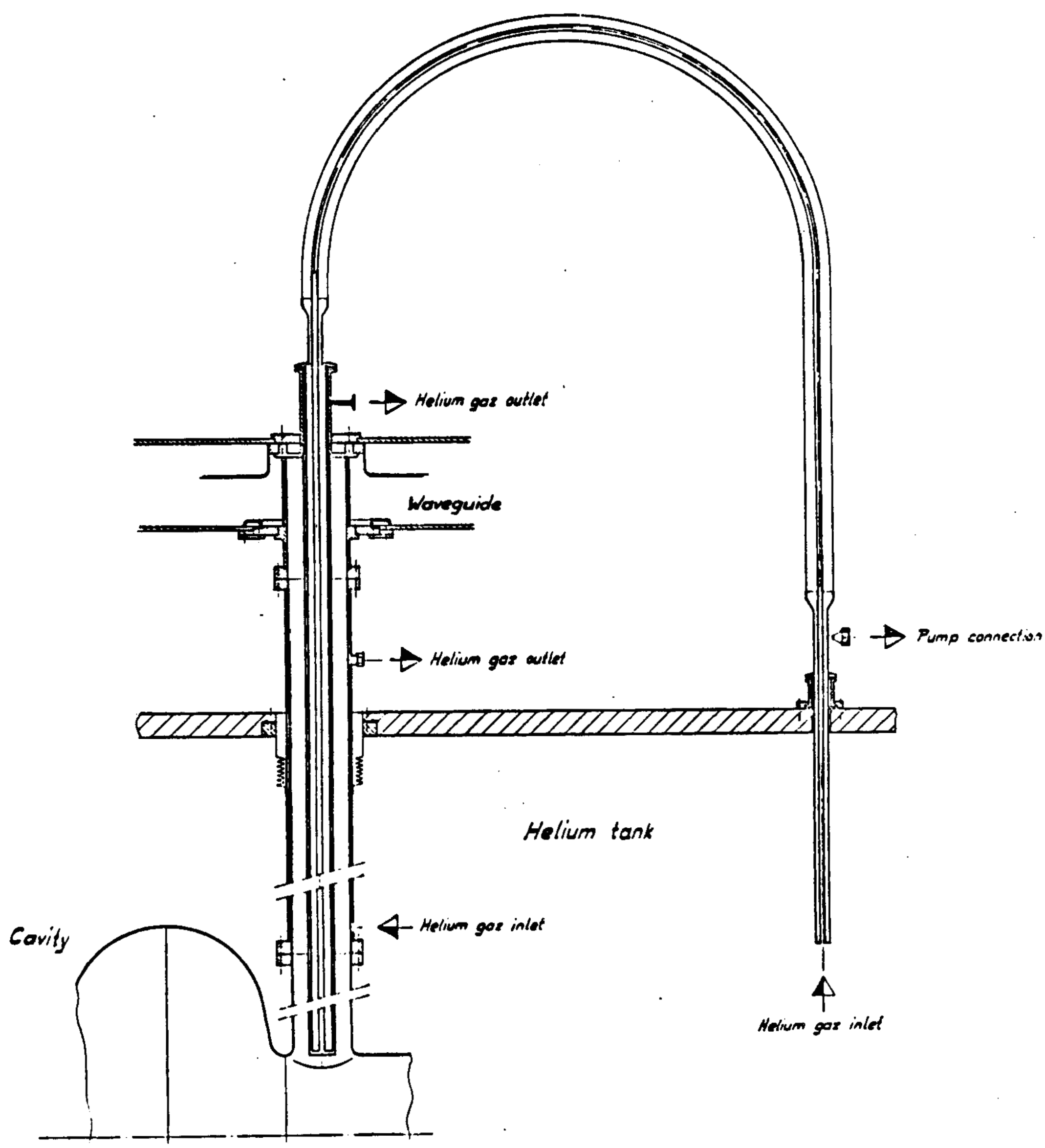

Fig. 18

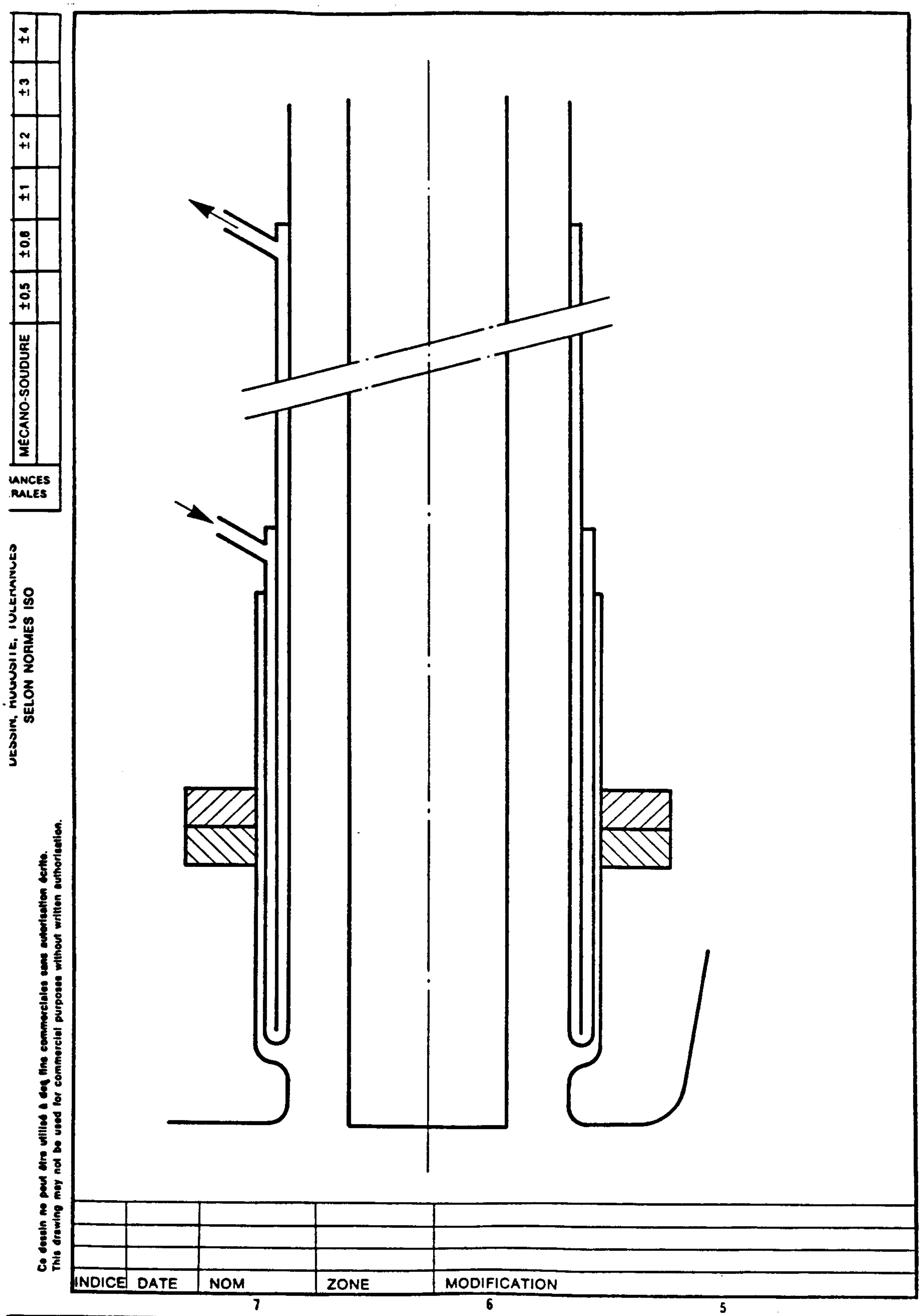
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Fig. 19

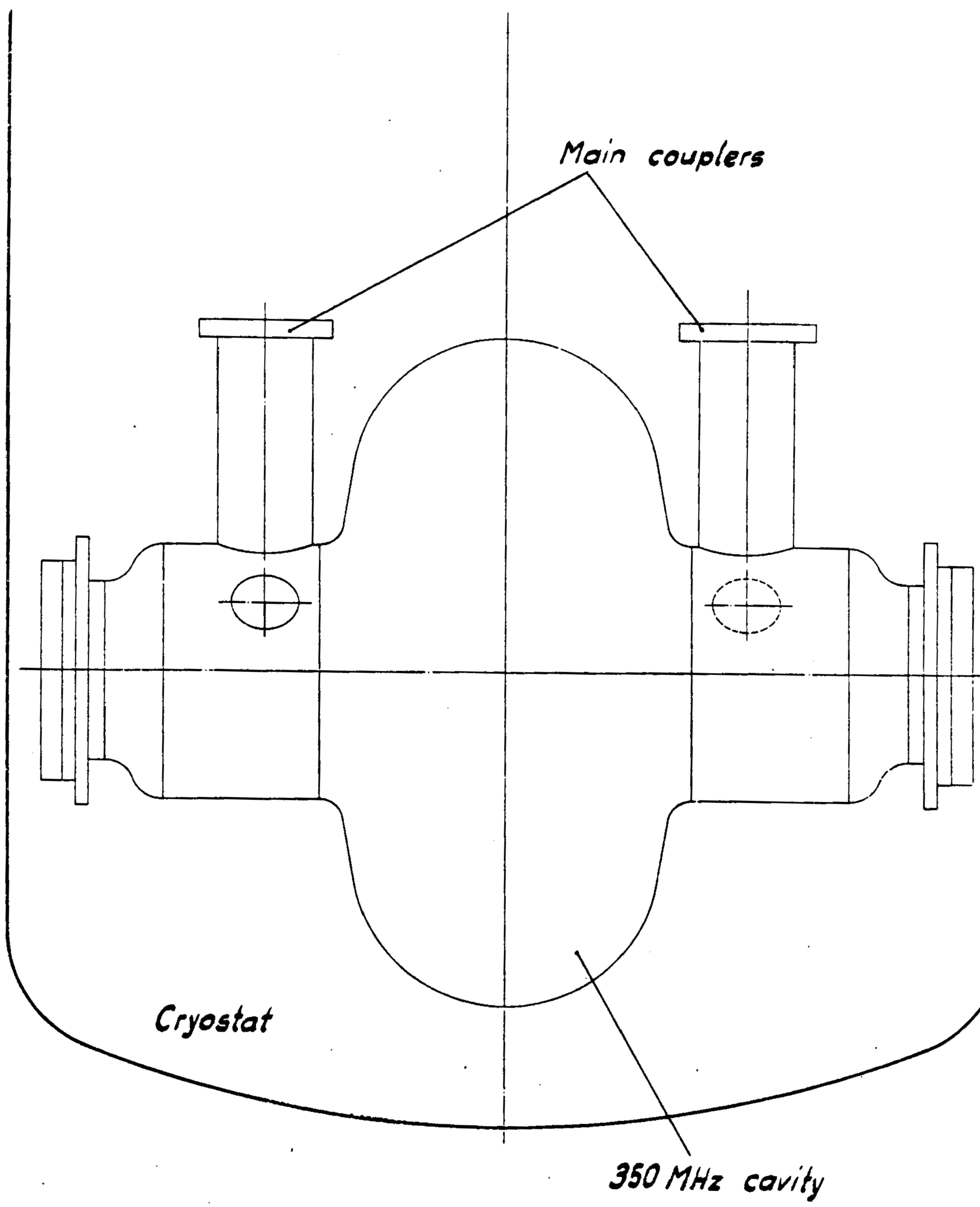

Fig. 20

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