COUPLERS – EXPERIENCE AT KEK

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I. Introduction

The R/D on the couplers for the TRISTAN superconducting cavities started in 1981. The first couplers developed for the beam test of a 3-cell SCC in 1984[1)], where the main purpose was to get basic data for the stable operation in the TRISTAN Main Ring (MR), were on-cell coaxial couplers shown in Fig. 1. In this beam test, HOM study was carefully carried out and the results showed good agreements with the theoretical calculation. The maximum transferred power to the beam was only 4 KW because of poor cooling for the coupling loop of the input coupler.

The design study of the couplers for the 5-cell SCC was continued and completed in 1984. These were on-beam pipe coaxial antenna couplers like other laboratories and tested in the TRISTAN Accumulation Ring (AR) in February 1986[2)]. The input coupler was tested up to 82 KW under total reflection condition, but the maximum transferred power to the beam was 26 KW due to the limited time for the tuning of the SCRF control system to increase the beam current.

The last beam tests with two 5-cell SCCs were carried out in 1987 ~ 1988. In these beam tests, the SCRF system stored the single bunch current of 69 mA, accelerated 25 mA with a field gradient of 5.7 MV/m and transferred the RF power of 86 KW to the beam. The maximum HOM power extracted by one HOM coupler was estimated to be about 3 KW.

The configuration of the couplers on 5-cell cavities is shown in Fig. 2 and 3. Two on-cell antenna HOM couplers are added to the AR cavities because of high beam current in the AR. For the MR cavities, all N-type ceramic connectors are thermally insulated by 50 Ω coaxial lines made of SUS pipes and set in the insulation vacuum. HOM power is extracted to outside through a 1/4" semirigid cable.

In this paper, our experiences in designing, testing and operating the couplers for 32 MR cavities are described.

II. Input Couplers for the TRISTAN MR Cavities

II.1 Requirements from MR operation

The input couplers have been designed under the following operating conditions.

A.	Beam current	$(2e^- + 2e^+) \times 4$ mA
B.	Over voltage ratio at the flat top	1.3
C.	Operating field gradient at the flat top	5 MV/m

So the optimum coupling Qin is 1×10^6 and the beam power is 92 KW.

In the view of RF power consumption, Qin of $1 \pm 0.5 \times 10^6$ is quite acceptable. But in practice, the followings must be taken into consideration.

1. Higher Qin makes the beam voltage V_{br} larger, then the maximum current might be limited by static Robinson instability at the injection energy where the cavity voltage V_c is small. It also needs higher generator power P_g of rather fast rise time to switch on RF again with a circulating beam at the flat top.
2. Lower Qin needs higher P_g to confirm the maximum field gradient Eacc,max.
3. Large difference in Qin,s of cavities driven by one generator makes unbalance in cavity voltages, and then the total voltage might be limited by the cavity having the lowest Eacc,max.

These are well understood by the following equations.

Robinson stability limit $$V_{br} < \frac{V_c}{\cos\phi} \qquad (1)$$

Cavity voltage $$V_c = V_{gr} - V_{br}\cos\phi$$

$$= 2\sqrt{P_g\left(\frac{R}{Q}\right)Q_L} - I_b\left(\frac{R}{Q}\right)Q_L\cos\phi \quad , \qquad (2)$$

where
V_{gr} : generator voltage
ϕ : synchronous phase angle
Q_L : cavity loaded $Q \simeq Q_{in}$
I_b : total beam current

Our solution to relieve Robinson stability limit is to introduce an artificial cavity tuning offset $\alpha(<0)$. Then Eq. (1) and (2) are modified as follows.

$$V_{br} < V_c\frac{2\sin\phi}{\sin2(\phi-\alpha)} \qquad (3)$$

$$V_c = V_{gr}\cos\alpha - V_{br}\cos\phi \qquad (4)$$

The validity of Eq. (3) for the beam oscillation of lower frequency than the cavity band width has been confirmed quantitatively in the last beam test[3].

On the other hand, Eq.(4) gives the possibility to lower the operating voltage of the cavity having the lowest Eacc,max among the cavities driven by one generator. Let Q^*_L and α^* be a loaded Q and a tuning offset of this cavity, then the voltage of this cavity V^*_c becomes

$$V^*_c = 2\sqrt{P_g\left(\frac{R}{Q}\right)Q^*_L}\ \cos\alpha^* - I_b\left(\frac{R}{Q}\right)Q^*_L\cos(\phi-\alpha+\alpha^*) \quad , \qquad (5)$$

where ϕ of the other cavities is assumed to be unchanged.

So by making Q^*_L lower or $|\alpha^*|$ larger V^*_c can be lowered, and by combining them it can be lowered independently on I_b.

Qin,s for our 32 cavities are 0.7 ~ 1.3 x 10^6. α,s for 16 operating cavities are -30° at the injection energy and usually -5° at the flat top. If there is a simple way to change Q^*_L or P^*_g freely from troublesome tuning for the phase of the input power, it is very helpful.

II.2 Design

The input coupler for the MR cavity is shown in Fig. 4 and in Photo.1. It consists of a coupling port on a beam pipe having a diameter of 18 cm, a 50 Ω coaxial line, a coaxial ceramic window and a doorknob type waveguide-coaxial transformer.

The coupling port has a diameter of 10 – 12 cm and is set 8 cm apart from a cell end. The typical Qin is 1 x 10^6 with a projection of a coupling antenna, which is made of OFHC copper and has a diameter of 52 mm, by 14 mm into the beam pipe. The field enhancement at the port edge normalized by the cavity surface peak field, E/Esp, is about 0.15, and the measured RF loss around the top of the antenna is about 8 W at the field gradient of 3 MV/m.

The inner conductor is mainly made of OFHC copper pipe having a diameter of 52 mm and a thickness of 1 mm. The outer conductor is made of 2.5 mm thick stainless steel. These are copper plated by 30 μm. The heat conduction is larger than the radiation, then the inner conductor can be cooled by water. The outer conductor is connected with a port flange by an indium ribbon and with a ceramic window by a conflat flange. No special cooling is necessary for the outer conductor.

The ceramic window is a coaxial disk type made from Al_2O_3 of 95 % purity. This has a rather large size of 170 x 42 x 10 mm^3 and is cooled by water. The window is set 95 cm apart from the port edge, about the middle between the detuned short and open plane. For the latter window, the vacuum side of the ceramic is TiN coated by about 60 Å and a view port for arc detection is set between the ceramic and the conflat flange.

The doorknob is made of 1 mm thick copper sheet so that it can absorb the geometrical mismatch. A polyethylene coaxial centering disk between the window and the doorknob works also as a backup when the ceramic breaks.

II.3 High power processing

A pair of delivered couplers is firstly rinsed with acetone and demineralized filtered water in an ultrasonic bath, though this process does not seem helpful to reduce RF aging time. Then the couplers are mounted on a test stand, evacuated and baked at about 125°C for more than 2 days.

The test stand shown in Photo.2 is a simple waveguide-coaxial probe transformer and works as a vacuum vessel. It has two view ports just below the couplers for arc detection.

The couplers are tested up to about 200 KW under the vacuum of $< 5 \times 10^{-6}$ Torr. Before adopting TiN coating, MP around the ceramic window has started from about 15 KW and it has take 4 ~ 13 hours to reach 200 KW. The number of arcing has been 0 ~ 100 times. After coating, MP does not occur below 50 KW, aging time and the number of arcing are reduced to 2 ~ 5 hours and 0 ~ 20 times respectively. RF losses measured by the temperature rise of cooling water are about 80 W for the inner conductors and usually less than 100 W (70 ~ 300 W) for the windows at the transmitted power of 150 KW.

Before cooling down the cavities, the couplers are tested again up to 60 ~ 75 KW under total reflection condition. MP around the coupling port occurs in the power level between 10 ~ 30 KW and above 50 KW. This causes the vacuum pressure rise and electrons are observed by the biased RF monitor probe. It takes 1 ~ 6 hours to process this MP, and that it is necessary before almost every cooling down.

II.4 Operation and summary

Up to now 46 input couplers have been made and tested for 32 MR cavities and 3 AR cavities. Among them, 8 windows have leaked. Classification of the testing conditions is given in Table I.

Table I. Summary of the high power processing

	Numbers of Tested Couplers	TiN Coating	Arc Detection	Numbers of Leaked Windows
Test Stand	24	No	No	4
	10	No	Yes	0
	12	Yes	Yes	0
Cryostat at room temp.	28	No	No	0
	10	Yes	No	1
at 4.4°K	38	Yes/No	No	3

The arc detection looks helpful to prevent accidents and TiN coating is effective at least to reduce the aging time at the test stand.

One window which has leaked at 4.4°K shows a visible crack (Photo.3A) and has contaminated the cavities, but the polyethylene disk has prevented a large amount of air flowing into the cavities and LHe boiling. This accident has happened during the cavity aging and at the RF power level higher than tested at the room temperature. In another case at 4.4°K, leak has occurred during the operation. No crack is seen in this ceramic window (Photo.3B)

16 cavities have been kept at 4.4°K for 5000 hours and the accumulated time used for the physics run amounts to 3100 hours[4]. With the average field gradient of 4.4 MV/m and a current of 10 mA, the RF power is 40 ~ 70 KW per coupler. Neither the degradation of the power capability nor the change of the temperature rise of cooling water has be observed until now.

III. HOM Couplers for the TRISTAN MR Cavities

III.1 Requirements from MR operation

The HOM couplers have been designed so that they could damp sufficiently both longitudinal and transverse modes excited by a beam current of ($2e^- + 2e^+$) x 4 mA. In Table II, dominant and well assigned HOMs of the TRISTAN 5-cell SCC are summarized. For the transverse modes, (R/Q) values calculated at 5 cm off axis are also given.

Table II. HOMs of the TRISTAN 5-cell cavities

Mode		Frequency (MHz)	(R/Q) (Ω)	$(R/Q)_T$ (Ω/m)	k: Loss Parameter (V/pC)
TM_{011}	4/5π	922	≲0.3		
	3/5π	928	1.2		0.002
	2/5π	935	22		0.032
	1/5π	942	56		0.083
	0	944	103		0.153
TM_{012}		~1500	≲30		≲0.07
TM_{013}		~2150	≲20		≲0.07
TE_{111}	1/5π	650	0.4	5.9	
	2/5π	659	0.7	10	
	3/5π	673	25	350	
	4/5π	689	32	450	
	π	706	8.9	120	
TM_{110}	π	717	1.1	15	
	4/5π	730	13	170	
	3/5π	739	26	340	
	2/5π	743	7.2	93	
	1/5π	745	0.03	0.4	
TM_{111}		~1000	≲63	≲600	

Longitudinal Modes

The longitudinal coupled bunch instability has been scarcely observed in the MR with a current of 13 mA and 104 normal conducting cavities having a longitudinal HOM impedance of ~ 5 MΩ. This is due to statistical cancellation by many modes in many cavities and is expected also for our cavities, but stronger damping is required in consideration of HOM loss.

In the e+e- storage ring, loss due to some HOM is given explicitly by

$$\Delta W = k\frac{q^2}{T} \times$$

$$\frac{1-\exp(-2\tau)+\exp(-\tau_-)\{\cos\delta_- -\exp(-\tau)\cos\delta_+\}+\exp(-\tau_+)\{\cos\delta_+ -\exp(-\tau)\cos\delta_-\}}{1+\exp(-2\tau)-2\exp(-\tau)\cos\delta} \qquad (6)$$

where $\tau_\pm = T_\pm/T_f$, $\delta_\pm = T_\pm(\omega-\omega_0)$

$T = T_+ + T_-$, $\delta = \delta_+ + \delta_-$, $\tau = \tau_+ + \tau_-$

and
- k : loss parameter
- q : charge in one bunch, assumed to be equal for every e^+, e^- bunch
- T : time interval between e^- (or e^+) bunches
- $T_\pm$: time interval between $e^\pm$ and $e^\mp$ bunches
- T_f : filling time of the HOM
- ω : angular frequency of the HOM
- ω_0 : angular frequency of the operating RF

The distance of the cavity center from the intersecting point is a multiple of a half wave length of the operating RF.

$$d = n\frac{\lambda_0}{2} \qquad (7)$$

Then the condition that the resonance buildup can occur is

$$\omega = l\omega_b \qquad \cos\delta = 1 \qquad (8)$$

and

$$\omega = \frac{m}{n}\omega_0 \qquad \cos\delta_\pm = 1 \qquad (9)$$

In the MR operation with ($2e^-$ + $2e^+$) bunches, the beam frequency ω_b is $\omega_0/2560$, so the resonance occurs if the frequency of the HOM is equal to the frequency given by Eq. (8) or (9) with integers, l and m, which satisfy

$$\frac{m}{n} = \frac{l}{2560} \qquad (10)$$

Generally it is very rare case. In our case, frequencies of the dominant TM_{011} modes have been confirmed to be free from the resonance but some arrangements of cavity location have been done to make sure.

Then the expected HOM loss is that for a single pass, and is about 170 W in < 1 GHz and ~ 100 W in higher frequency range with a current of ($2e^-$ + $2e^+$) x 4 mA.

The resonance might happened for a beam of $2e^-$ or $2e^+$. But an impedance of 2MΩ, which gives a HOM loss of 128 W, is not so large.

Transverse Modes

The maximum tolerable transverse impedance calculated from the theoretical work[5)] for the coupled bunch instability is ~ 20 MΩ/m with a beam of $2e^-$ or $2e^+$ x 4 mA in the MR. But in the case where many cavities are used, the frequencies of HOMs are distributed in both damping and untidamping side of the beam frequency. This statistical cancellation pushes up the tolerable impedance for one mode to ~ $20/\sqrt{N}$ MΩ/m, where N is a number of dominant modes in all cavities.

In the TRISTAN MR, this is still too small to be attained, so a feedback system with a damping time of about 300 μsec has been prepared by the first stage of the operation. However in practice, 104 normal conducting cavities having an impedance of ~ 50 MΩ/m have not caused the transverse instability without the feedback system. So 50 MΩ/m is sufficient also for our cavities.

III.2 Design and Performance

The MR HOM coupler made of Nb is shown in Fig. 5. Two couplers are set on the other beam pipe from the input coupler and inclined by ± 45°. They have a coaxial L-C filter for the accelerating mode and a T-stub to cool the coupling antenna.

The projection of the antenna into the beam pipe is 21 mm on the average, which gives the coupling Q of 4×10^4 and 8×10^3 for TM_{010} and TM_{011} of a single cell cavity. The measured loaded Q and the resultant impedance for the dominant modes in TM_{011}, TE_{111} and TM_{110} of 32 cavities are shown in Fig. 6 and 7.

0 and 1/5π modes of TM_{011} are excited mainly in end cells in our 5-cell cavities. Then the difference of geometry in two end cells makes the concentration of the field for two modes in an opposite end cell each other. In order to damp 0 mode more strongly than 1/5π mode, the width of the equator straight section is shortened by about 0.5 mm in the end cell of HOM coupler side. 0 modes having higher impedance than 2 MΩ in Fig. 6 are those of the failed cavities in this tuning.

Two couplers have a filter with different dimensions so that there is no stop band as a whole. Dimensions, calculated stop band frequencies and other parameters are summarized in Table III, and the broad band responses of two filters are shown in Fig. 8.

Table III. Parameters of two filters

	Type A	Type B
Diameter of the inner cylinder	44 mm	44 mm
Length of the inner cylinder	112 mm	102 mm
Diameter of the outer cylinder	64 and 86 mm	60 and 90 mm
Length of the T-stub	78 mm	90 mm
Second stop band	1950 MHz	2250 MHz
Third stop band	2950 MHz	3200 MHz
Fourth stop band	4200 MHz	4500 MHz
Stop band of T-stub	n x 1950 MHz	n x 1650 MHz
For the fundamental mode		
Hmax when the maximum C-gap field is 1 MV/m	1100 A/m	1100 A/m
Δf/capacitive gap distance	11 MHz/mm	17 MHz/mm

The tuning of the fundamental frequency is done by cutting the top of the inner cylinder by 0 ~ 0.5 mm. The sensitivity is 5 MHz/mm. The other fine tuning is possible by controlling the time of chemical polishing with usual 1:1:1 mixture. The sensitivity of this process is 20 and 35 KHz/μm for Type A and B. The distribution of the fundamental filter frequency for 64 HOM couplers is shown in Fig. 9. The band width at –50 dB is about 1 MHz, where the Q for the accelerating mode is about 2×10^{10}.

III.3 High Field Performance and Operation

During the aging of the cavities in the horizontal cryostat, 2 phenomena, MP and breakdown at the filters are observed. The maximum field gradient ever reached is 9.4 MV/m.

Two side MP at the capacitive gap occurs in the cavity field gradient between 0.3 ~ 1.0 MV/m for Type A and 0.2 ~ 0.6 MV/m for Type B. This is observed as a vacuum pressure rise, a temperature rise of carbon resistors and an increase of the output power from the HOM coupler due to the change of the filter frequency. The RF processing of half an hour is needed after each cooldown. Though it is rare case, MP revives during the operation by adsorbed gases, and needs the RF processing.

Breakdown has happened in several HOM couplers at the field gradient higher than 5 MV/m, where the estimated Hmax in the filter is about 4000 A/m. The RF loss of more than 50 W warms up and expands the inner cylinder and then changes the filter frequency. An output power of about 1 KW has been observed with a time constant of about 10 minutes. In two cases a power of more than 1 KW has melted the pin of the N type connector in the vacuum vessel. It is once or 3 times at most if it happens. An interlock module against the breakdown of the HOM couplers is in preparation.

In the last operation, the beam current has been limited to 11 mA by the unexpected temperature rise of few N type connectors, especially by two melted connectors mentioned above. This is due to loose and unstable pin contact and lack of convection cooling. Although all semirigid cables and N connectors have been tested in the vacuum up to the RF power of 180 W from a 500 MHz amplifier, this has been not enough for higher frequency and longer period. All 64 N connectors will be replaced by larger 15 D size ceramic connectors and semirigid cables will be removed in the next summer shutdown.

The measured HOM power is 50 ~ 80 W per coupler with $(2e^- + 2e^+)$ x 2.5 mA, where 60 ~ 75 % comes from the frequency component lower than 1 GHz, 75 ~ 90 % from < 1.8 GHz and almost 0 from > 4 GHz. No beam instability caused by SCC has been observed up to a single bunch current of 4 mA or a total current of 11 mA.

IV. RF Monitor Couplers

A coaxial monitor coupler shown in Fig. 10 is set just below the input coupler, and is used also as a pickup probe for field emitted electrons. The coupling port has an opening of 15 mm and the probe is a stainless steel rod having a diameter of 4 mm and a length of 12 cm. Coupling Qs are 2 ~ 5 x 10^{11} with probe top positions of 6 ~ 8 mm inside the port edge.

Crosstalk between couplers and coupling between two cavities are measured by feeding the RF power through one input coupler. The biggest but negligible crosstalk is that between input couplers, and is -80 dB by power when both cavities are detuned and -60 dB when the power fed cavity is tuned. The coupling between two tuned cavities is 1 x 10^{-3} in field strength, which well agrees with a calculation.

Acknowledgements

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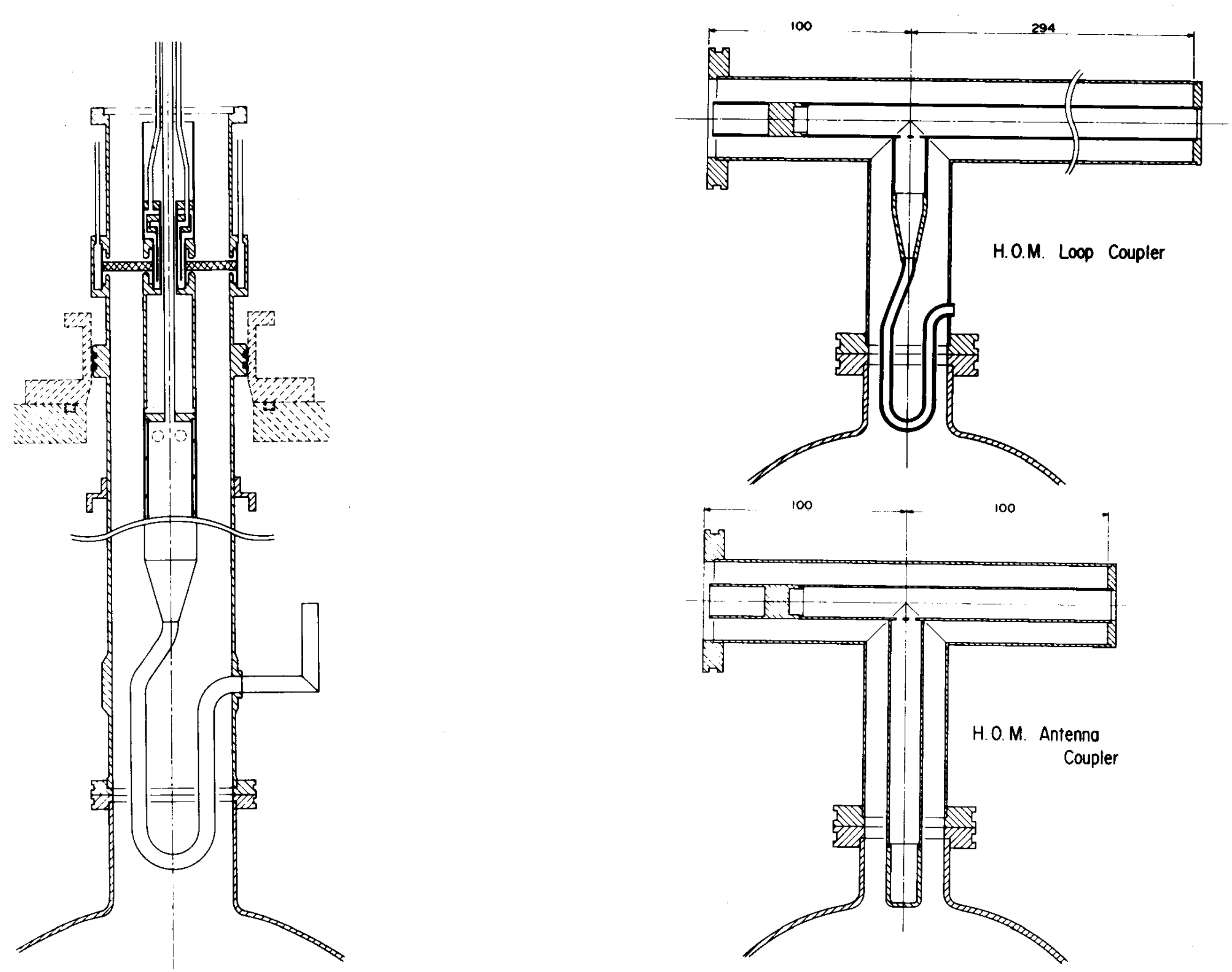


Fig. 1 On-cell Input (77D) and HOM Couplers for the 3-cell Cavity.

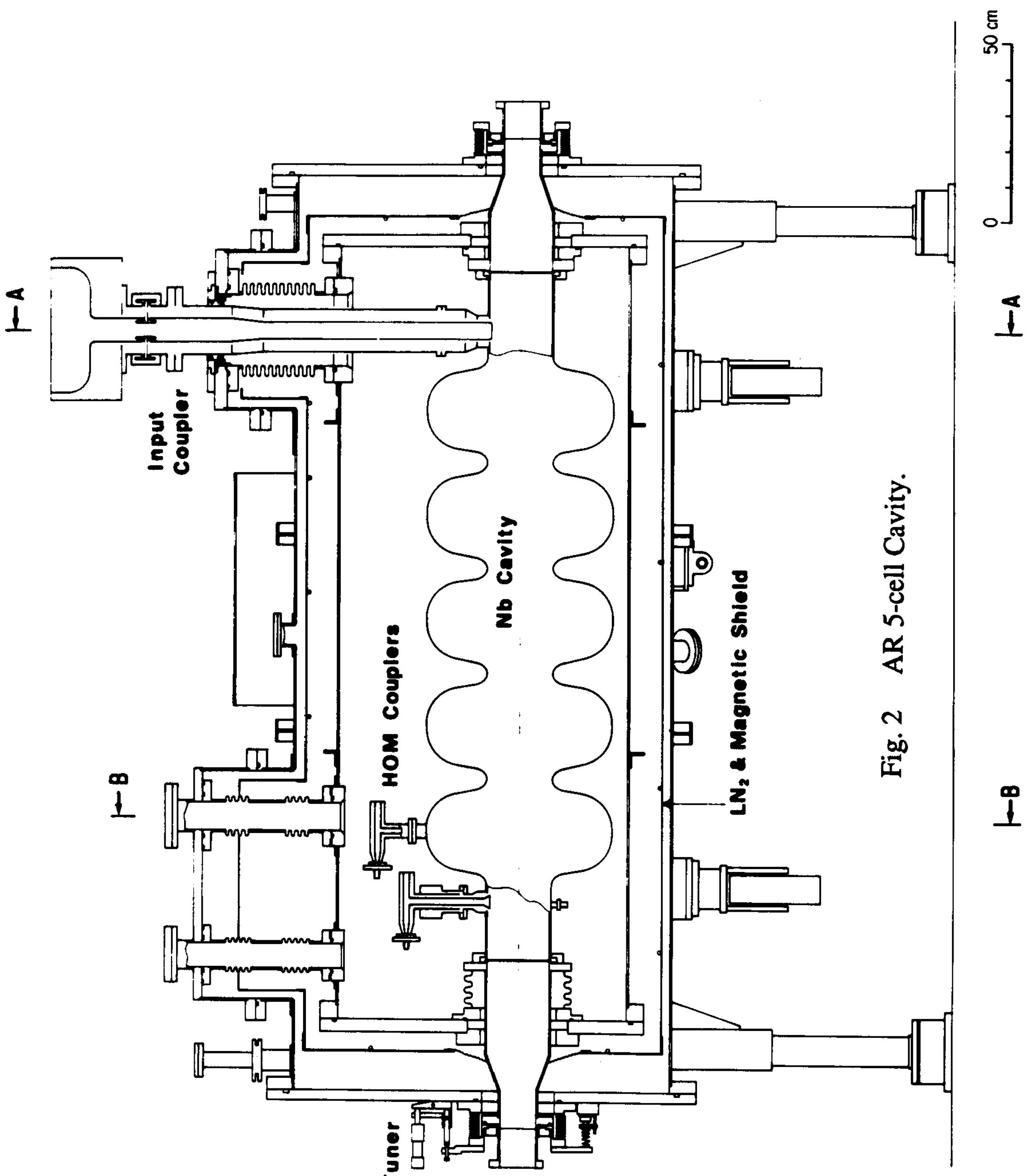


Fig. 2 AR 5-cell Cavity.

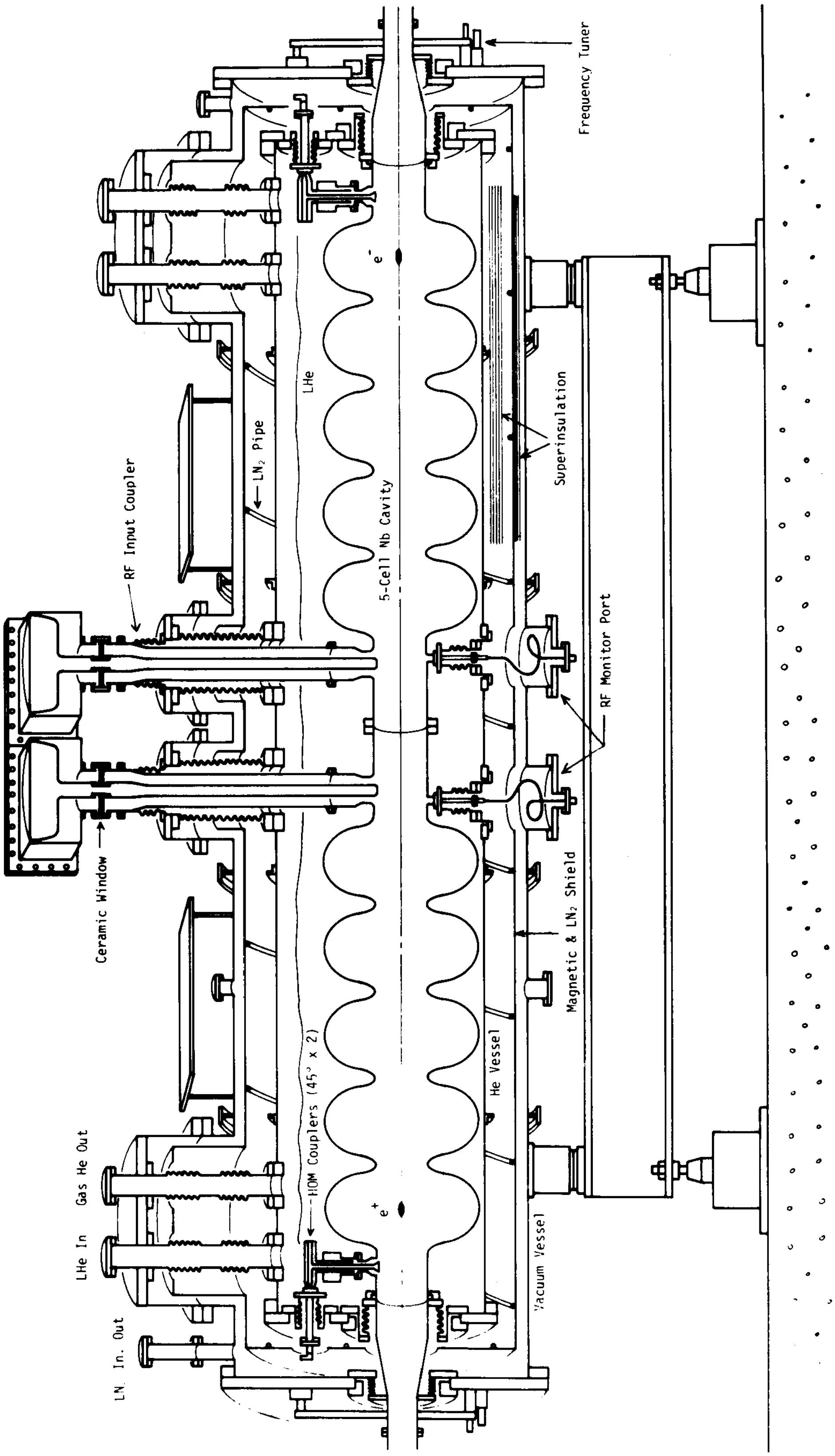


Fig. 3 A pair of the MR 5-cell cavities.

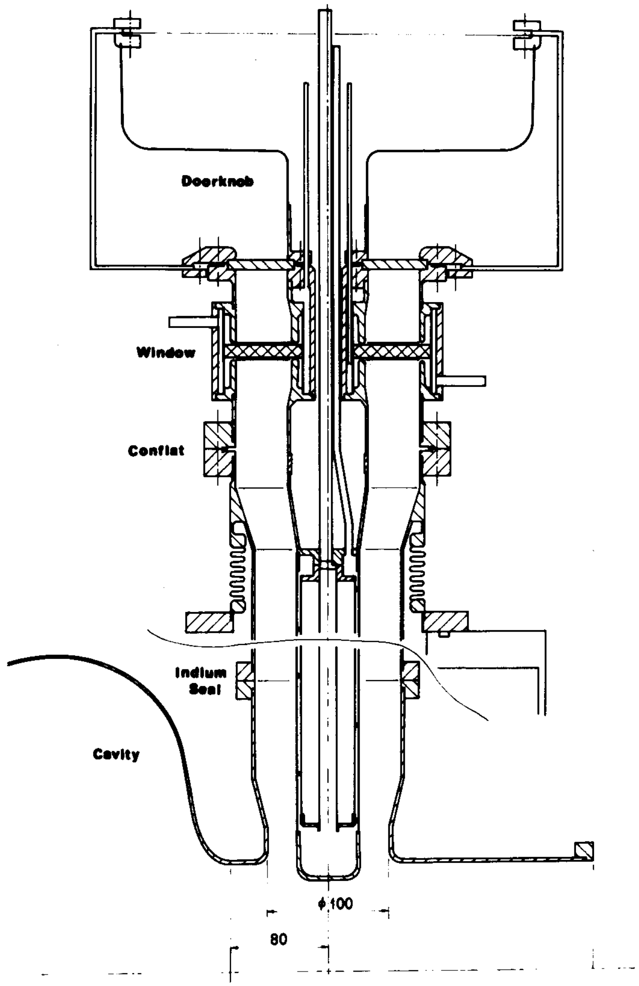


Fig. 4 Beam Pipe Input Coupler for the 5-cell Cavity.

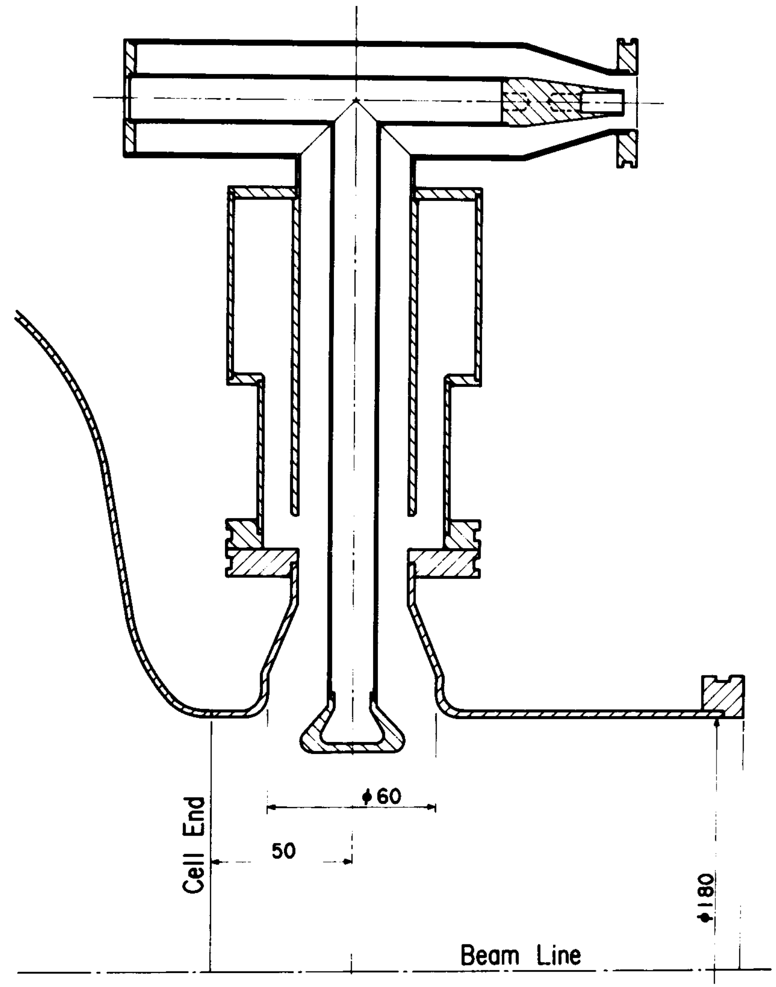


Fig. 5 Beam Pipe HOM Coupler.

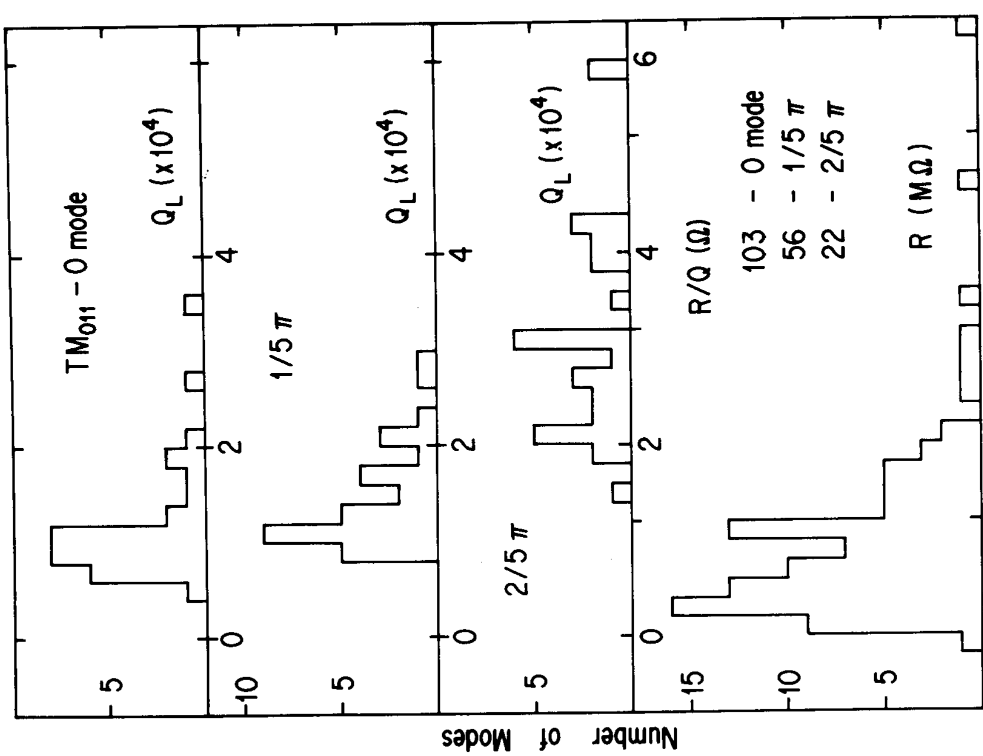


Fig. 6 Measured Damping of Dominant TM_{011} Modes.

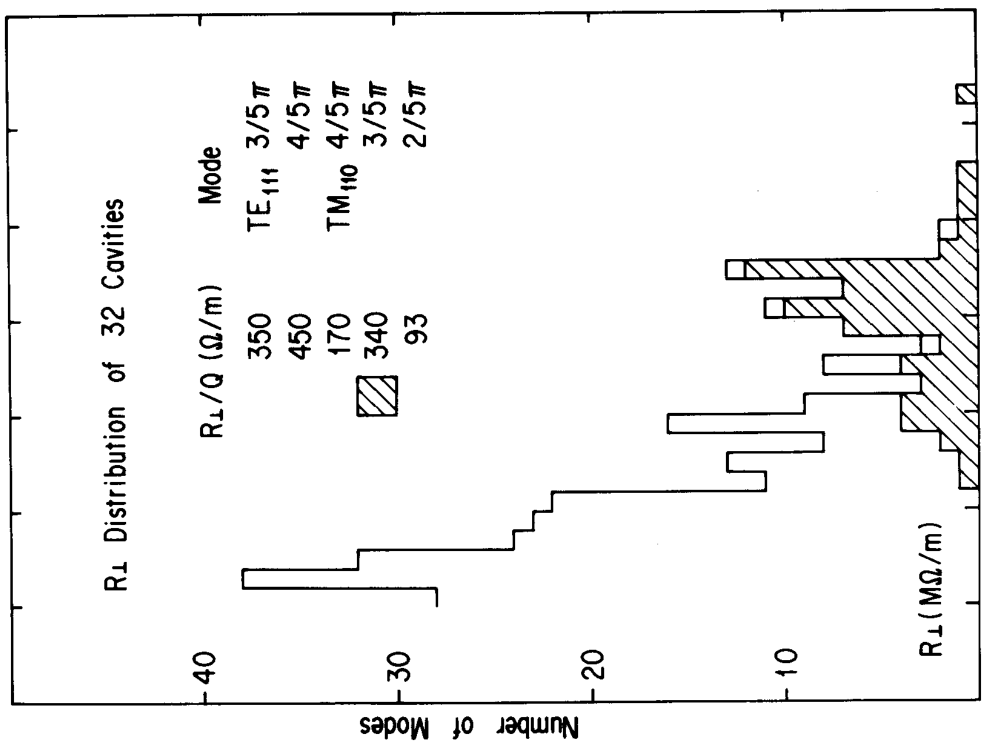
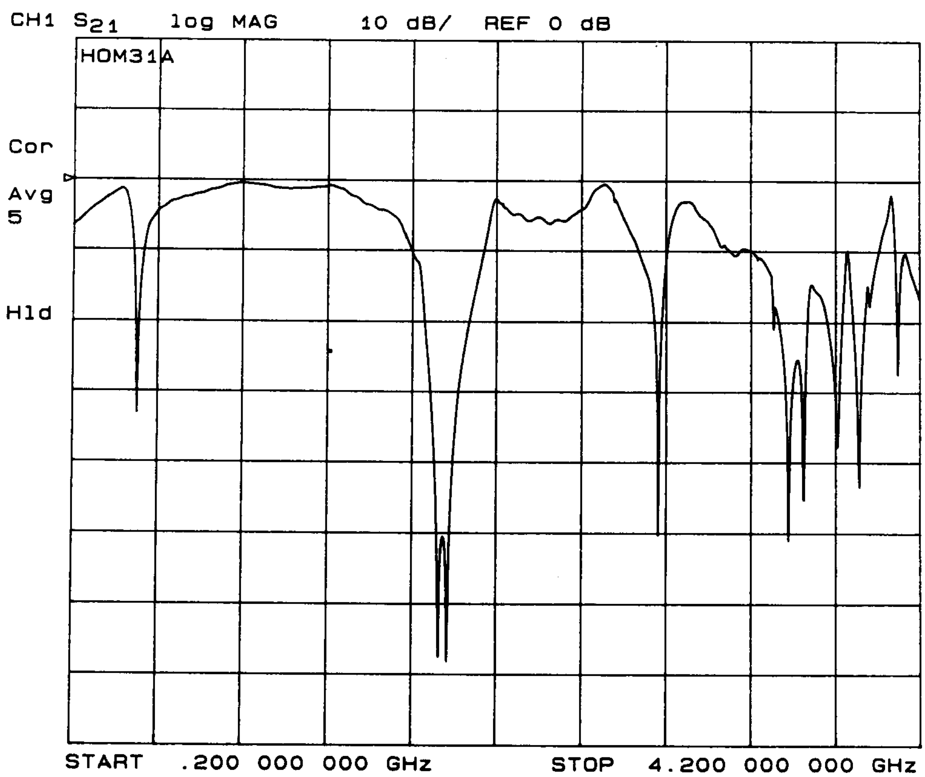


Fig. 7 Measured Damping of Dominant Transverse Modes.



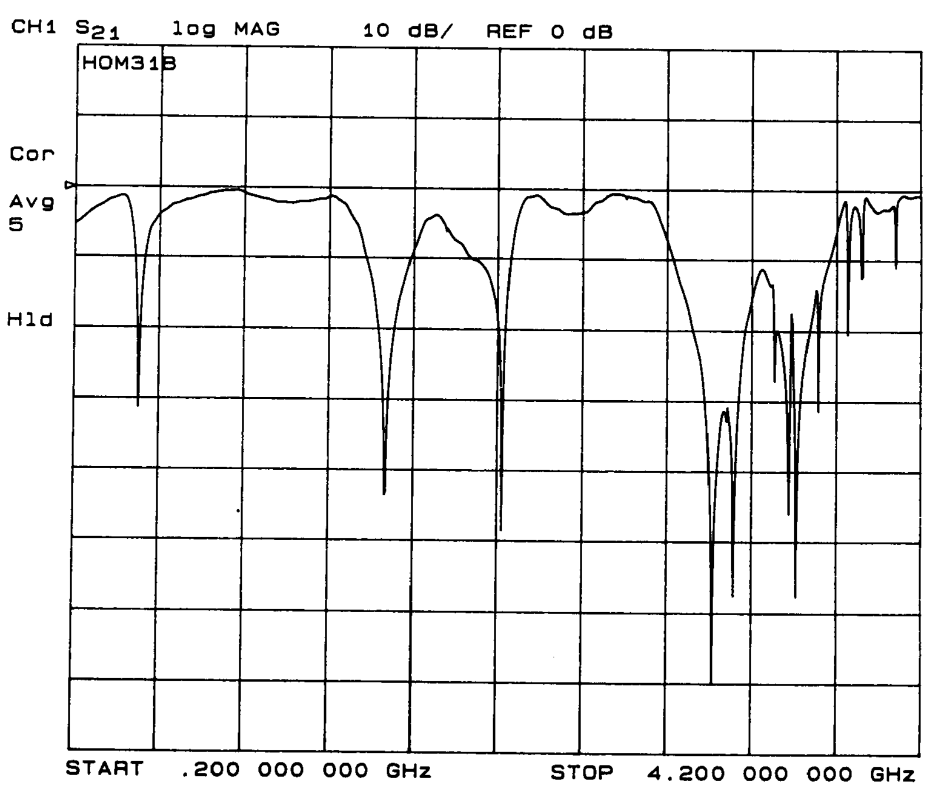


Fig. 8 Broad Band Response of the HOM Coupler, Type A (Upper) and Type B (Lower).

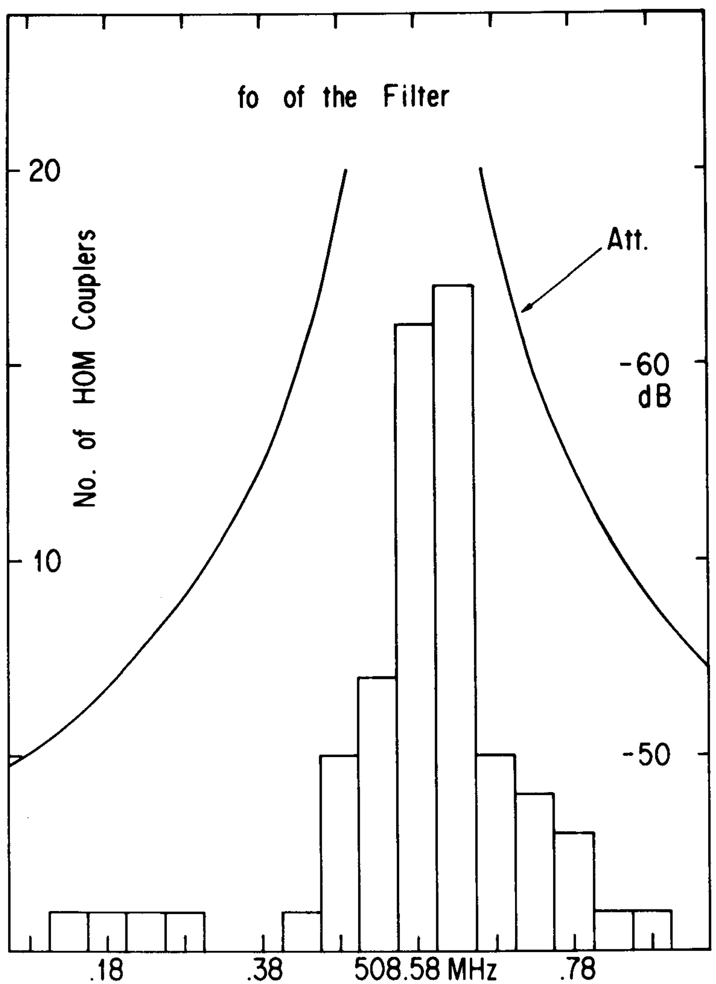


Fig. 9 Distribution of the Fundamental Filter Frequency.

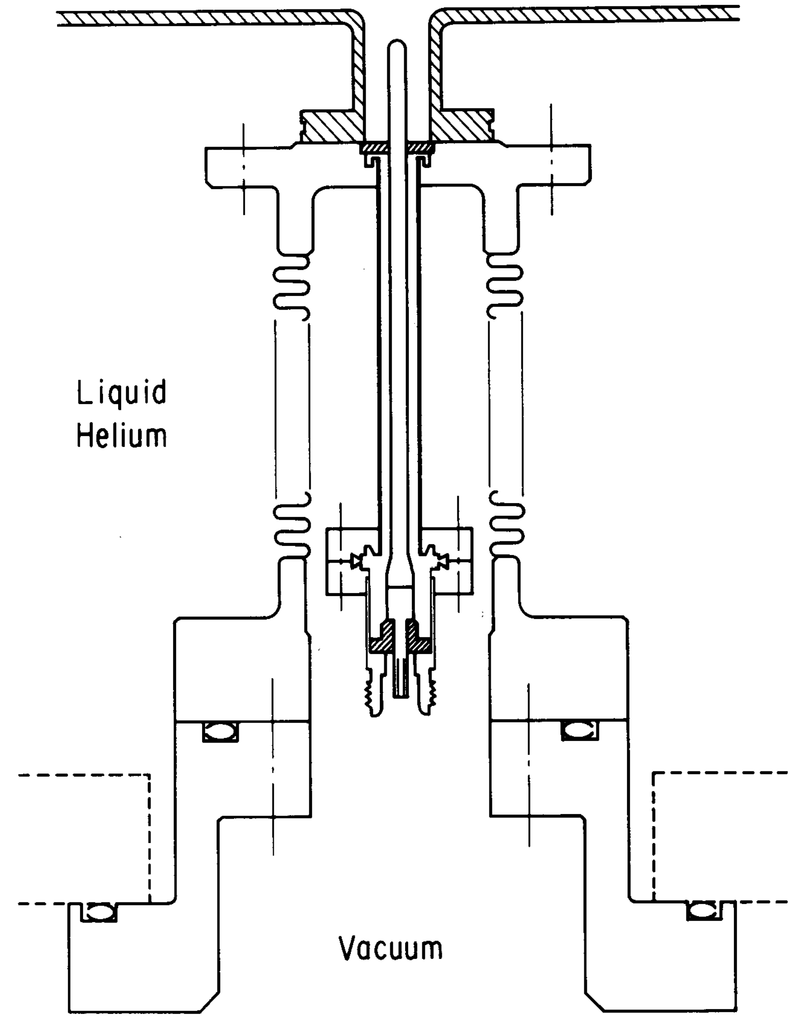


Fig. 10 RF Monitor Coupler with a N Type Connector.

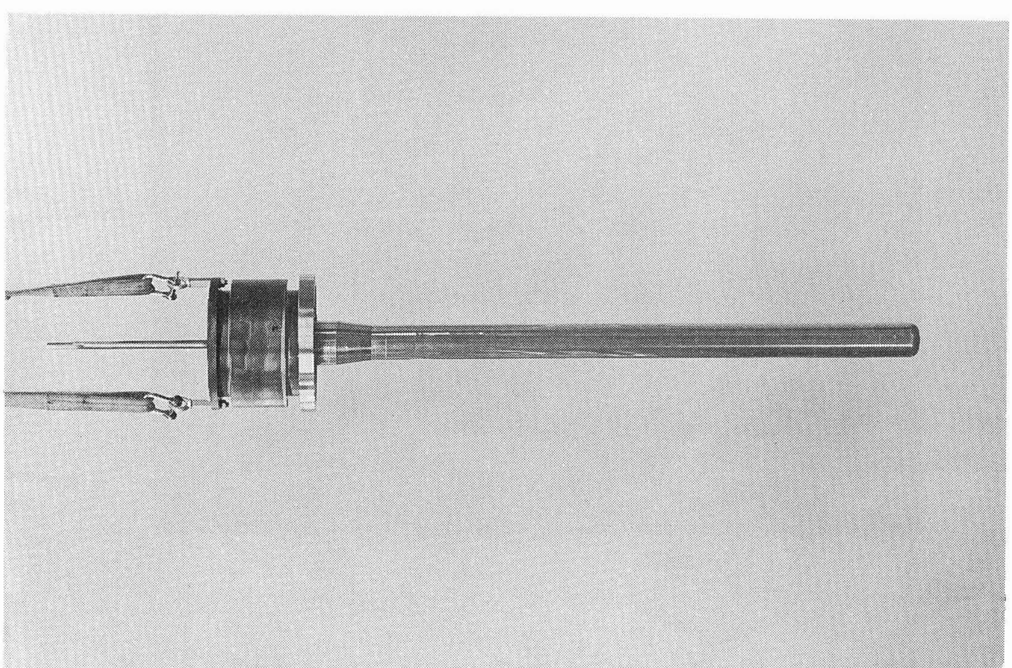


Photo.1 Ceramic Window and Inner Conductor.

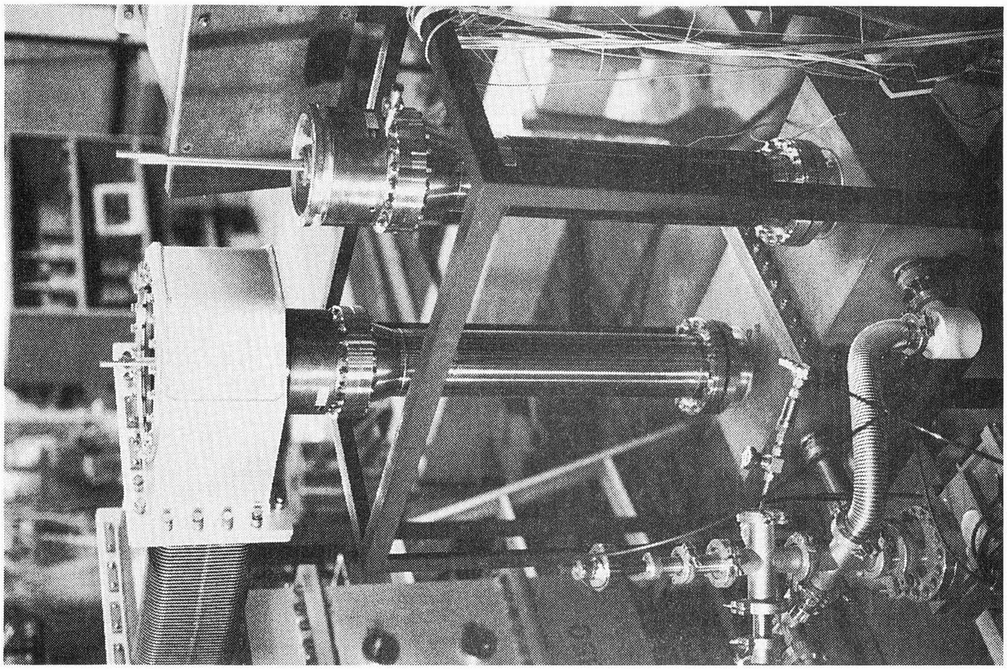


Photo.2 Test Stand and Two Input Couplers.

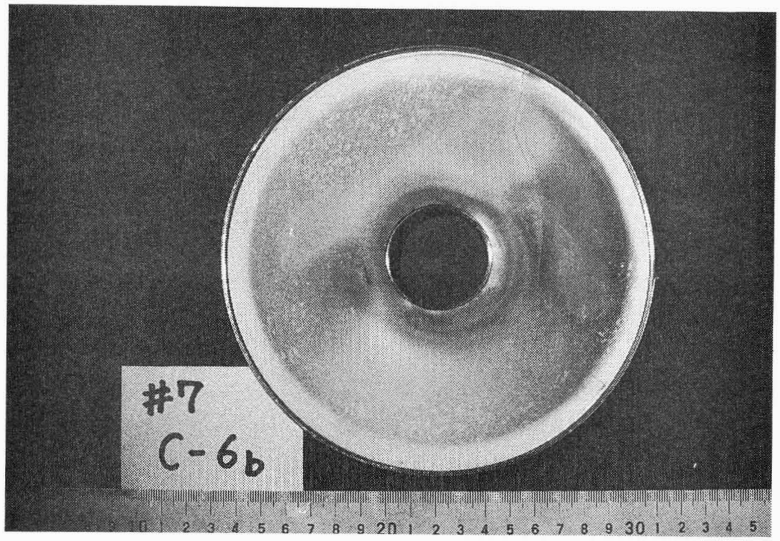


Photo.3A Cracked and Cu Sputtered Ceramic at 4.4°K.

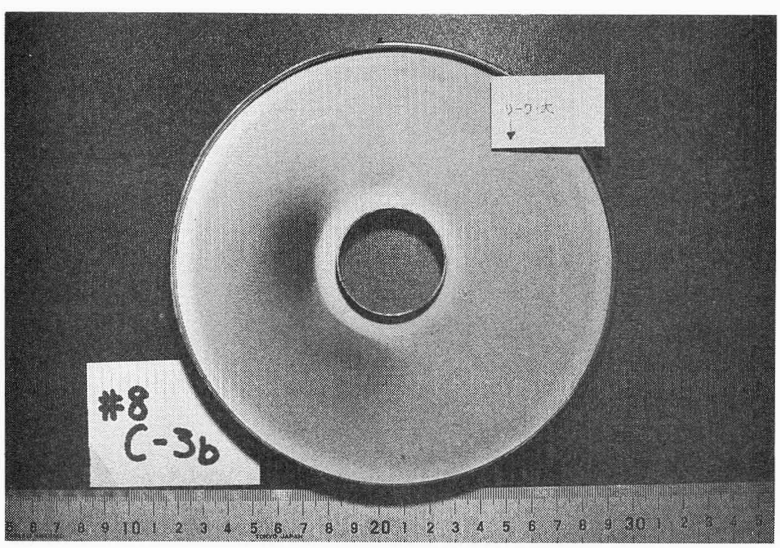


Photo.3B Leaked but not Cracked Ceramic at 4.4°K.