Storage Ring Beam Tests

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1. Introduction

Storage ring beam tests since the Second Workshop on RF-Superconductivity (July 1984) are discussed in this report. The experiments are listed in chronological order. Details depend on information given in papers and/or by private communication. A review of earlier tests is given by R. Sundelin in (1).

2. Overview

Year	Laboratory	Ring	Cells	f MHz	MV/m	Limitation	Ref
1982	Cornell	CESR	2 x 5	1500	1.9	MP	2
1982	Karlsruhe	PETRA	1	500	2.3	MP	3
1983	CERN	PETRA	5	500	2.1	Q	4
1984	KEK	TAR	3	508	3.5	Vac.	5
1984	KEK	TAR	3	508	4.1	coupler	6
1984	Cornell	CESR	2 x 5	1500	6.5 2.4	FE Q	7
1985	DESY	PETRA	9	1000	2.5	Q	8
1986	KEK	TAR	5	508	3.5	FE	9
1987	CERN	SPS	4	352			10
1987 ?	KEK	TAR	2 x 5	508			11
1987 ?	DESY	PETRA	2 x 4	500			12

Tab. 1: List of storage ring beam tests(MP = multipacting, Q = quench, Vac. = vacuum leck, coupler = excessive heating at input coupler, FE = field emission)

Tab. 1 presents an overview of storage ring beam tests carried out so far. The CERN 1987 beam test was under operation during the week of the workshop and the 1987 KEK and DESY beam tests were scheduled for October /November of this year. The maximum accelerating gradient as seen by the beam is listed as MV/m.

3. Description of Beam Tests

a. 1984 KEK Beam Test

In 1984 a 3-cell 508 MHz cavity has been tested twice in the Tristan Accelerator Ring (TAR). Three individual 1-cell cavities have been fabricated and tested. Afterwards a 3-cell cavity was produced using these three cells. A coaxial loop-coupler was mounted to the middle cell for input coupling (see Fig. 1). In total three higher order mode (HOM) couplers were mounted to the end cells:two antenna couplers and one loop coupler (see Fig. 2). Both types of couplers use a tuned stub to supress the fundamental mode frequency. The three cell cavity is assembled in a horizontal cryostat (see Fig. 3). Tuning is accomplished with a mechanical and two piezo electric tuners at room temperature. A refrigerator is used for cool down and 1000 LHe deware bufferes pressure oscillation during operation.

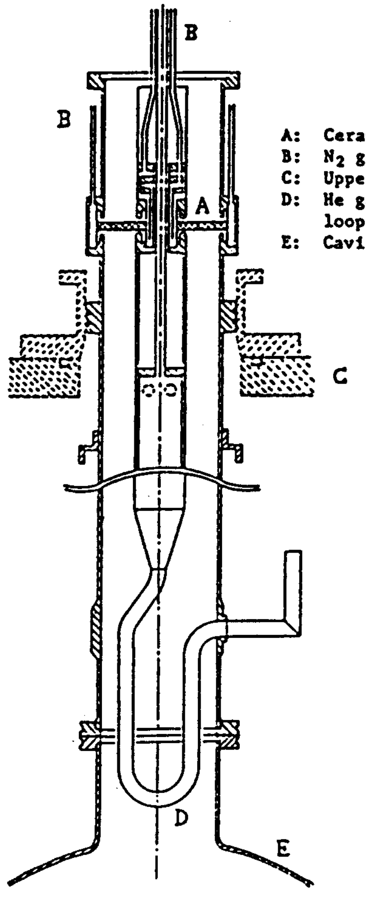


Fig. 1: Input loop coupler

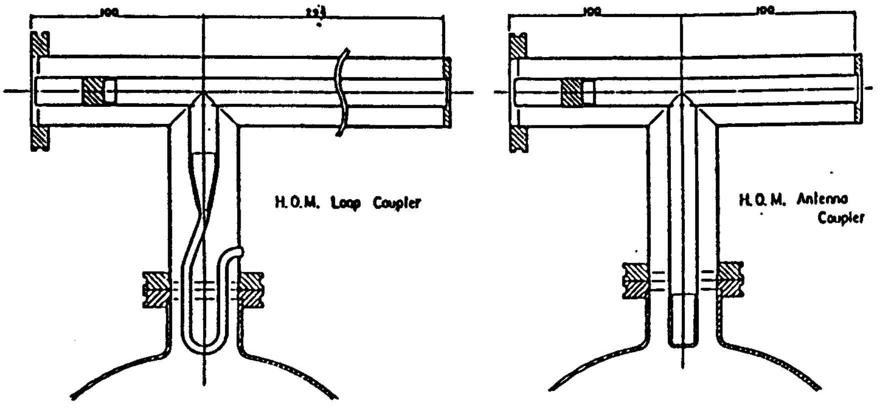


Fig. 2: Two types of HOM couplers

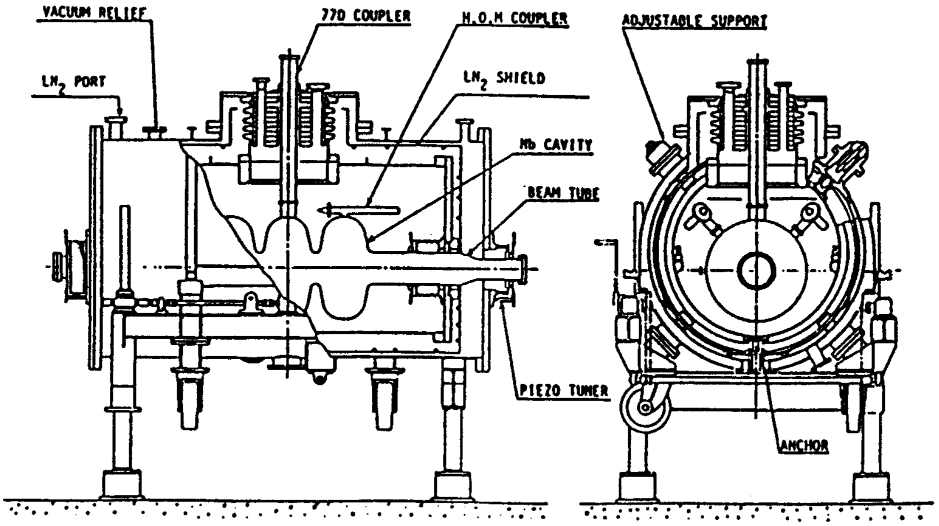


Fig. 3 Cross section of 3 cell KEK 1984 cryostat

Resonance frequency		508 MHz
number of cells		3
active length		0.88 m
r/Q		389 Ohm
E peak/E(acc)		1.89
H peak/E/(acc)		39.6 Gaus/MV/m
fundamental coupler	coaxial loop at middle cell	
Q(ext)	2.2×10^6 test # 1 1.3×10^7 test # 2	
HOM-couplers	1 x loop coupler, end cell a 2 x antenna coupler, end cell b	
typical HOM damping of dominant modes	TM_{011}	3×10^4
	TM_{020}	1×10^6
	TM_{021}	5×10^4
	TE_{111}	2×10^5
	TM_{110}	1×10^5
	TM_{111}	2×10^5
	TE_{112}	1×10^4
tuning:		mechanical +/- 250 KHz piezo +/- 1.5 KHz
pressure dependency		56 Hz/mbar
measured pressure fluctuation		1 mbar
cryostat		diameter = 1.1 m L = 2.1 m
static loss		12 W
rf loss		34 W at 3.7 MV/m

Table 2: Parameters of the KEK 3-cell cavity used in the 1984 beam test

First 1984 KEK beam test

The first beam test was carried out in May 1984. At an accelerating gradient of 3.5 MV/m a single bunch of 4.2 mA was captured at 2.5 GeV and accelerated to 5 GeV. At an increased gradient of 4 MV/m (without beam) a vacuum leak developed at the input coupler. Due to insufficient cooling overheating resulted in opening up a leak: dirty air, He-gas and water spoiled the cavity; in addition copper sputtered the input part. After the accident the coupler was repaired and the cavity was cleaned by H_2SO_4 rinsing in HF, H_2O and methanol.

Second 1984 KEK Beam Test

After the repair of the coupler a second beam test was carried out in July 1984. The maximum values reached were:

E(acc) = 4.2 MV/m limited by heating at input coupler
P(beam) = 4 kW; limited by heating at input coupler
I(beam) = 10 mA; limited by heating at gate valve

The HOM-behavior of the cavity was studied with single bunch operation:

- the HOM-power of longitudinal modes was measured and agreed with SUPERFISH calculation
- a transverse instability due to a TE_{111}-mode was observed at 3 mA which is slightly higher than predicted.

During the above mentioned measurements the HOM-modes were tuned to resonance (if possible) by moving the fundamental mode tuner.

b. Cornell Beam Test

At Cornell elliptically shaped 5 cell cavities at 1500 MHz have been developed for a possible use in CESR II. Input and output couplers are rectangular waveguides. Two windows, one Teflon window at room temperature and one ceramic window at LN_2-temperature seal the input waveguide. The HOM couplers were sealed by Kapton windows at 2.3 K and by Teflon windows at room temperature. The cavities were fabricated from RRR ca 100 Nb-material. Because of the high frequency of 1500 MHz the working temperature was 2.3 K. During the beam test in Nov/Dec. 1984 in CESR the following maximum data were reached:

E(acc) = 6.5 MV/m cavity # 1, limited by field emission
= 2.4 MV/m cavity # 2, limited by quench
P(beam) = 27 kW limited by coherent longitudinal dipol instabilities
I(beam) = 22 mA " " " " " "

The HOM power with single bunch operation was measured to 0.66 W per $(mA)^2$ as compared to 2.3 $W/(mA)^2$ by calculation. This discrepancy is explained by HOM-radiation into the beam line. The threshold of beam instabilities during tuning the cavity in 400 increments has been measured and compares reasonable with calculations. A motor at LHe-temperature was used to squeeze the input coupler waveguide, thus changing the coupling strength.

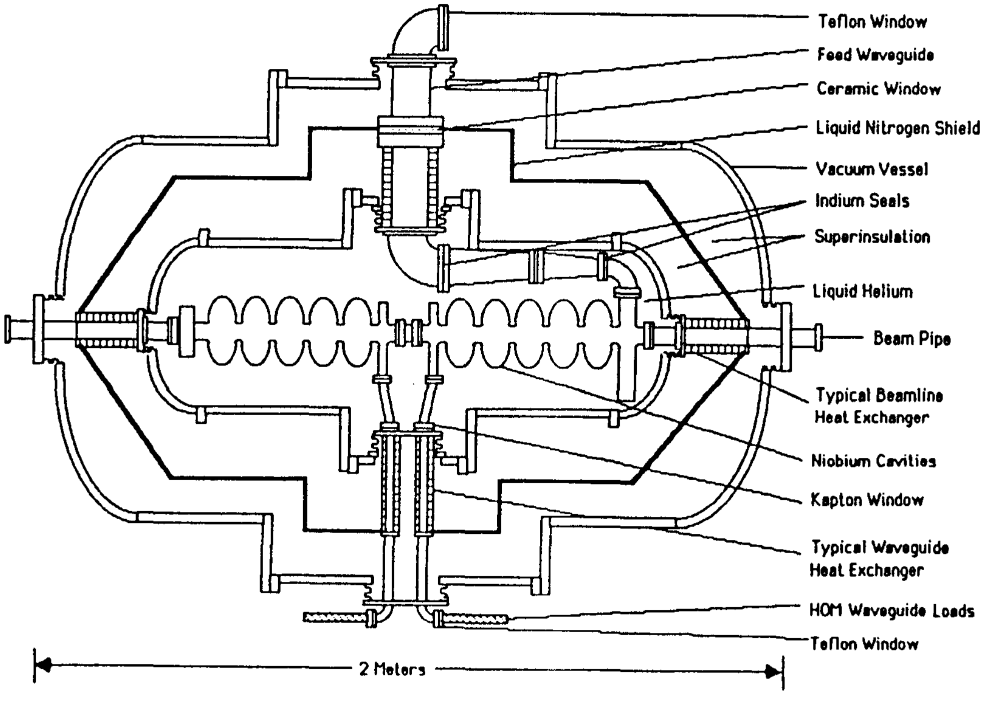


Fig. 4: Cross section of 1984 CORNELL beam test cryostat

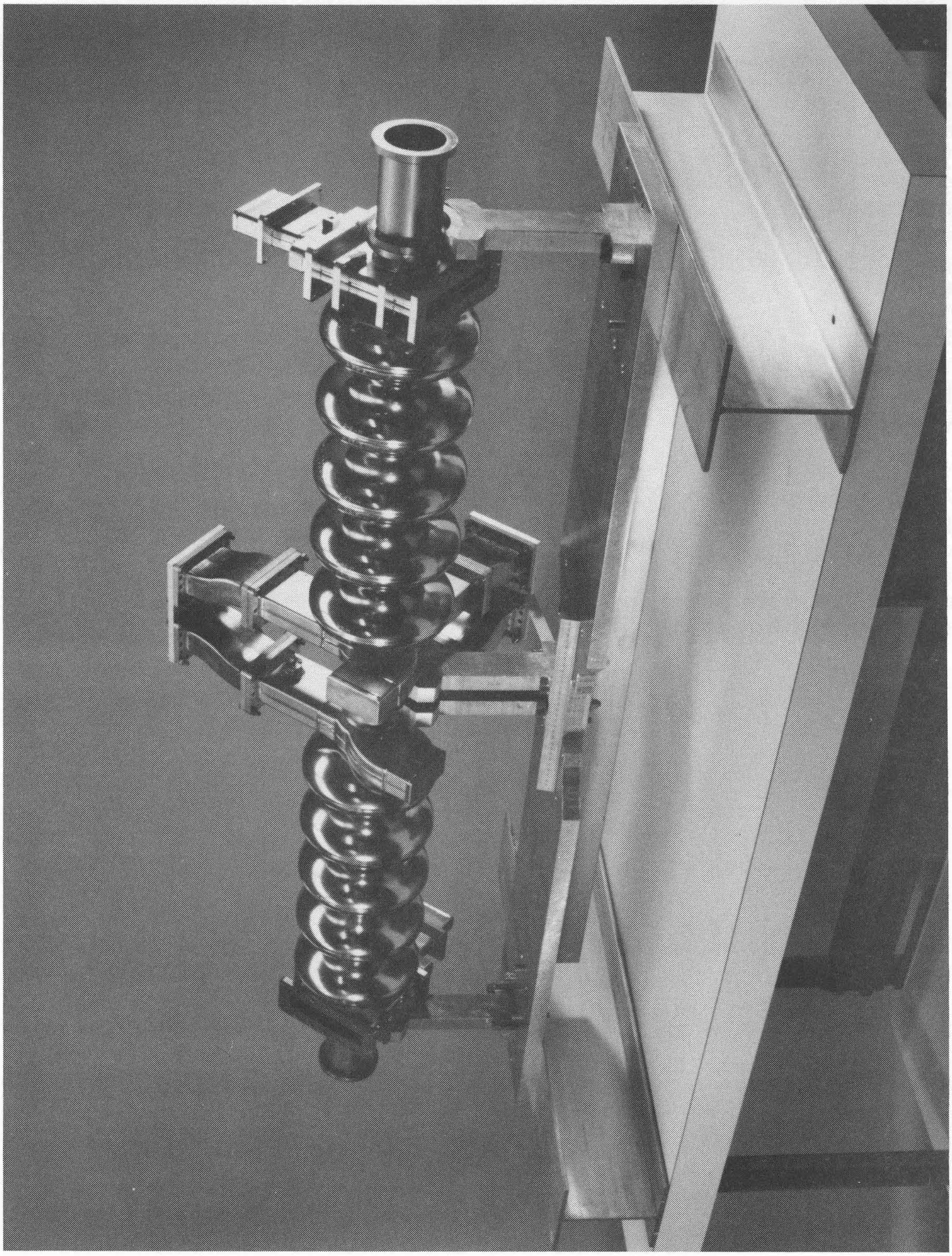


Fig. 5: 2 x 5 cells unit, fo = 1500 MHz, of CORNELL design

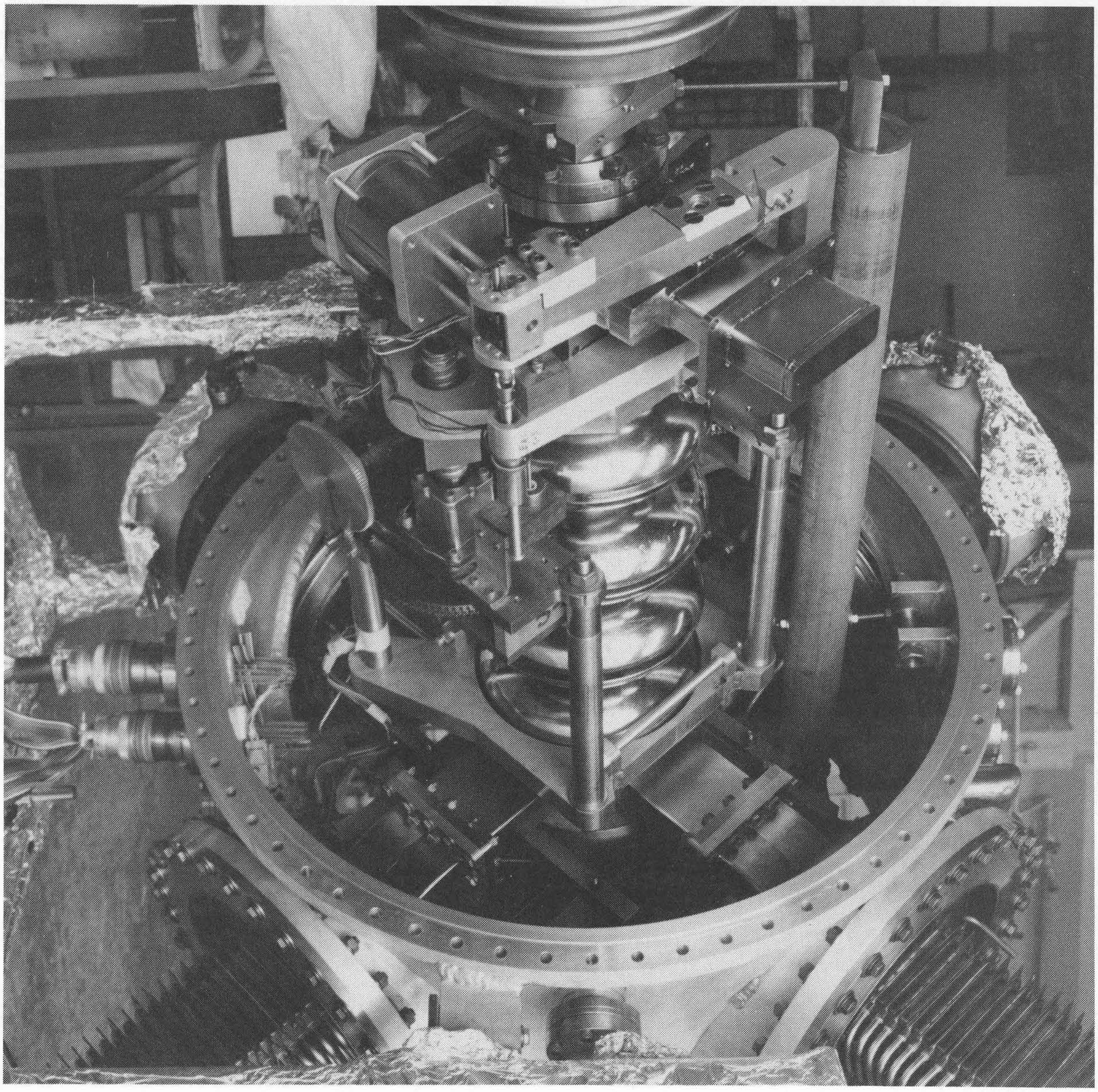


Fig. 6: CORNELL cavity during assembly

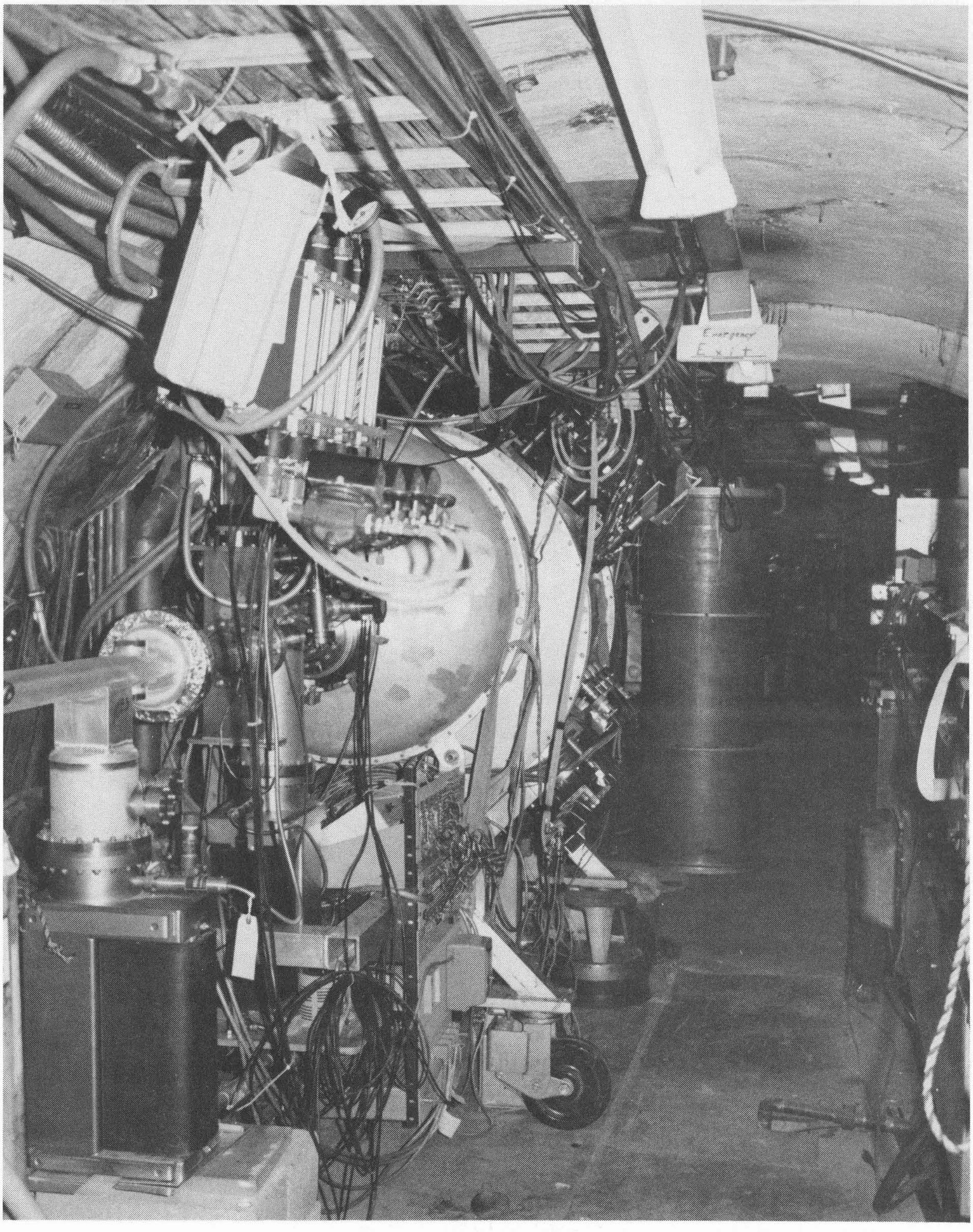


Fig. 7: Beam test cryostat of 1984 CORNELL test

After the beam test the low field cavity was inspected and a "dirt spot" (copper particle?) was detected. The cavity was cleaned by rinsing with detergent, water and methanol, but no acids. After the rinsing this cavity reached E(acc) = 12 MV/m limited by field emission loading.

resonance frequency		1500 MHz
number of cells		2 x 5
active length		2 x 0.5 m
r/Q		2 x 959 Ohm
E peak/E(acc)		2.56
H peak/E(acc)		46.8 G/MV/m
fundamental coupler		rectangular waveguide
Q(ext)		3 x 10^5
Window		Teflon (300 K), ceramic (2.3 K)
HOM-coupler		rectangular waveguides
typical damping of dominant modes	TM_{011}	0.8 x 10^3
	TM_{020}	2 x 10^3
	TE_{111}	3 x 10^3
	TM_{110}	6 x 10^3
tuning:		motor and gear box at 2.3 K
pressure dependency		
measured pressure fluctuation		+/- 0.5 mbar at 50 mbar
cryostat		diameter = 1.3 m L = 2 m
static losses		5.4 Watt at 2.3 K
rf losses		5.5 W at 6.3 MV/m, one cavity

Table 3: Parameters of the CORNELL 5 cell cavity used in the 1984 beam test

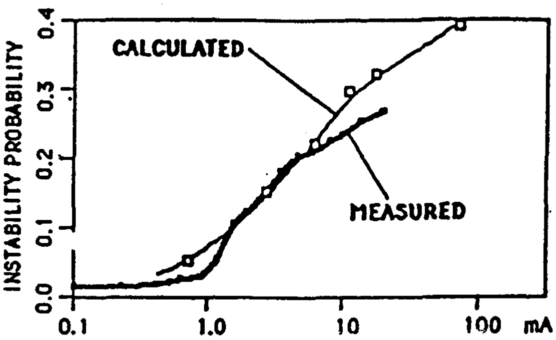


Fig. 8: Calculated and measured instability probabilities (CORNELL 1984 beam test)

c. 1985 Beam Test at PETRA

9-cell 1 GHz cavities have been developed at Desy to explore the possibility of upgrading the PETRA-beam energy. The cavities were fabricated from RRR = 25 Niobium. Fundamental and HOM-couplers used rectangular waveguides at both ends of the structure. The fundamental mode frequency is suppressed by cut off damping of the HOM coupler-waveguide. The HOM-power transmitted into the input waveguide is absorbed in a broad band feed line absorber. The input line window consists of a ceramic disk and a broad band transition from rectangular to circular rigded waveguide (see Fig. 10).

The cryostat containes two nine cell cavities (see Fig. 9). Each cavity is tuned lengthening or shortening the structure with a hydraulically driven system at room temperature. Due to a leak at an input coupler weld only one cavity was assembled for the beam test.

During the beam test the following maximum data were reached:

E(acc) = 2.5 MV/m limited by quench
P(beam) = 27.5 kW limited by sparking at feed line absorber
I(beam) = 8 mA (cavity active) limited by sparking at feed line absorber

The measured HOM-power at 12 mA (4 bunches, NL-cavities active, SL-cavity detuned for the fundamental mode) of 280 W agreed with the calculated value of 300 W (TBCI). One transverse instability was observed during the change of the Petra frequency (during ramping from 7 GeV to 21 GeV): one polarization of the TE$_{111}$ family showed insufficient damping (Q(ext) ca. 10^7) so that the beam was lost by a quench of the cavity (beam dump by cavity interlock). This problem could be overcome by changing the PETRA-frequency fast enough during crossing the HOM-resonance.

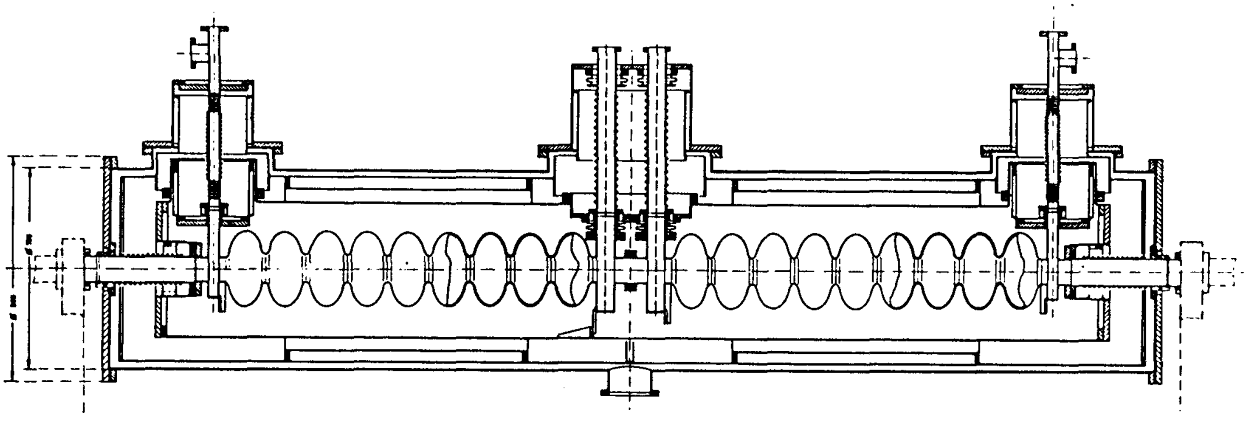


Fig. 9: Cross section of the 1 GHz DESY cryostat

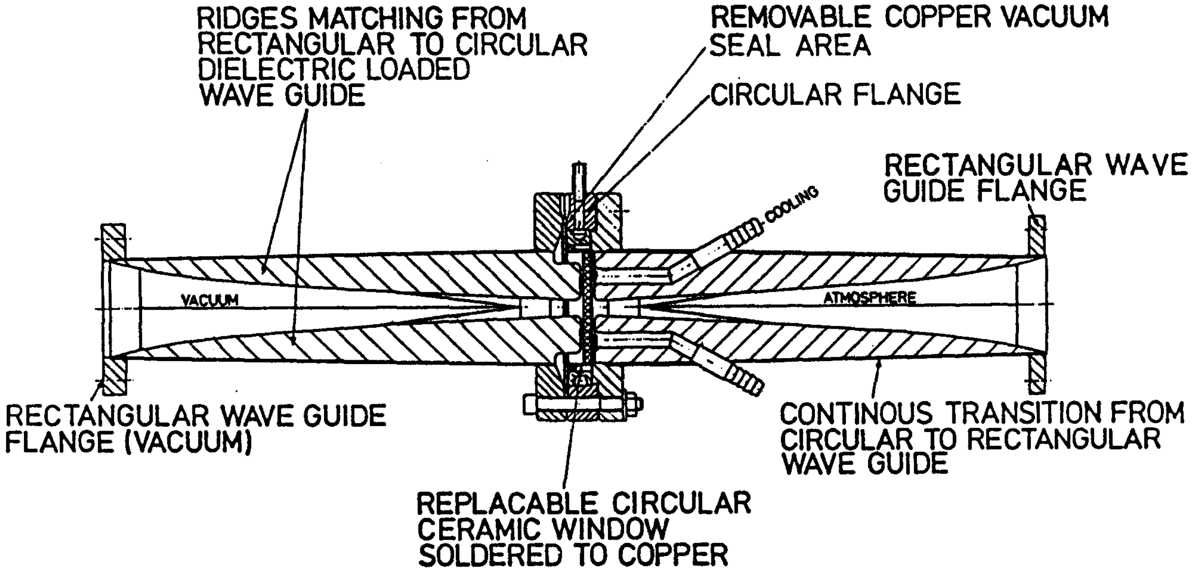


Fig. 10: **Broadband wave guide rf power feed window**

Resonance frequency		1 GHz
number of cells		9
active length		1.35 m
r/Q		1000 Ohm
E peak/E(acc)		1.8
H peak/E(acc)		43 Gaus/MV/m
fundamental coupler		rectangular waveguide at beam pipe
Q(ext)		1.3 x 10^5
window		disk in waveguide, 300 K
HOM-coupler		rectangular waveguide at beam pipe
typical damping of dominant modes	TM_{011}	5 x 10^3
	TM_{020}	1 x 10^4
	TE_{111}	3 x 10^3
	TM_{110}	4 x 10^4
tuning:hydraulic drive		+ 300 KHz, - 130 KHz
pressure dependency		- 23 Hz/mbar
measured pressure fluctuation		+/- 30 mbar/30 min
cryostat		diameter = 0.86 m L = 4.0 m
static loss		14 Watts
rf losses		16 W (at 2.5 MV/m/1 x 9 cell

Table 4: Parameters of the DESY 9-cell cavities used in the 1985 beam test.

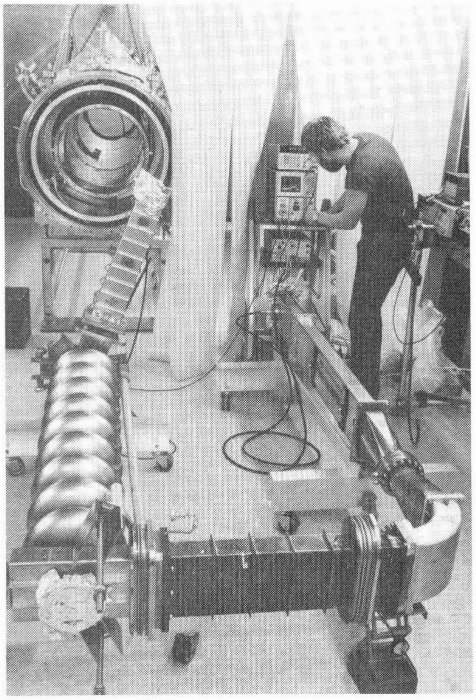


Fig. 11: 9 cell DESY cavity during rf measurements

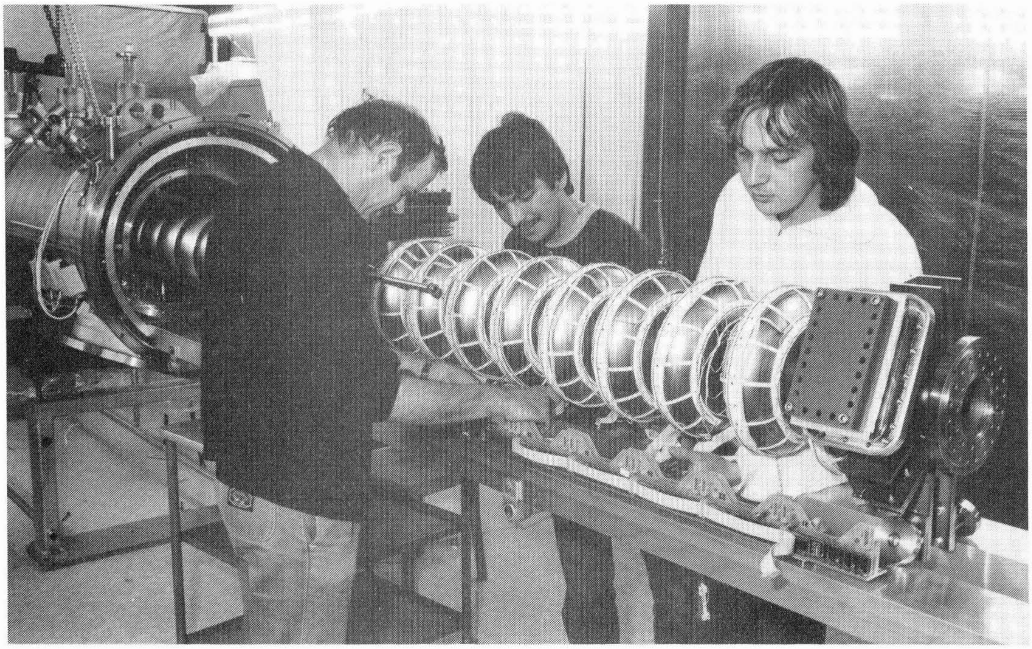


Fig. 12: 2 x 9 cell DESY unit with quench detector system

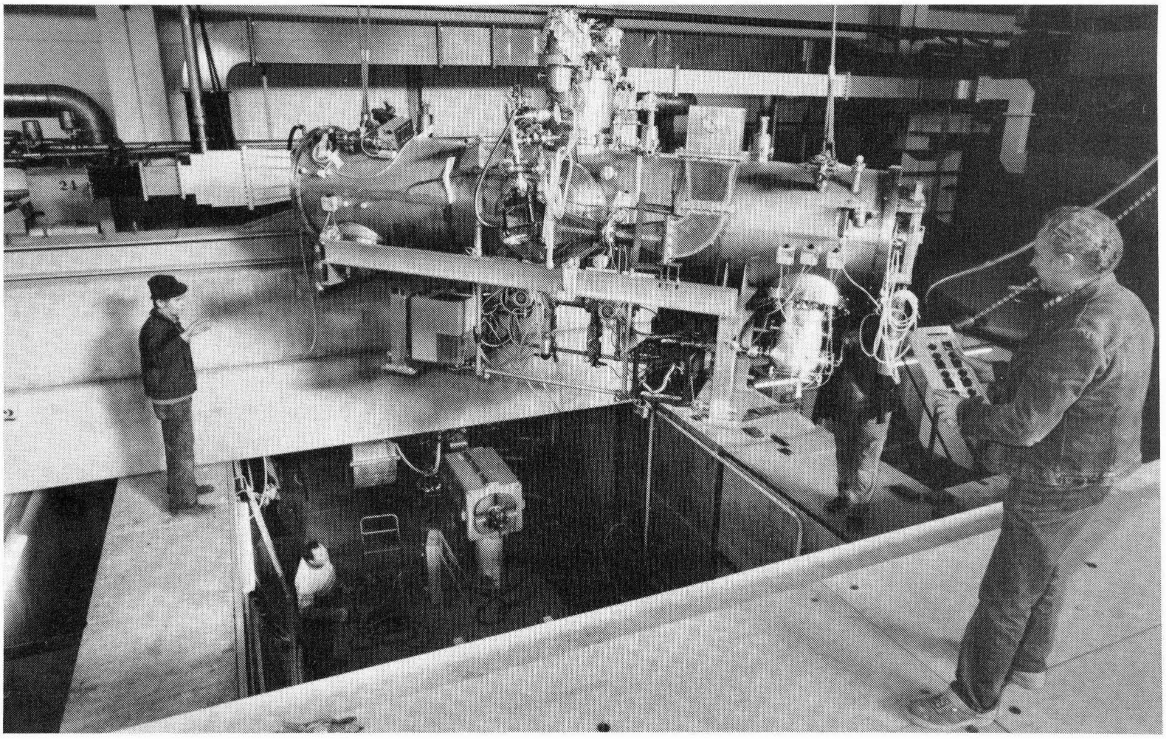


Fig. 13: 1 GHz cryostat during installation in PETRA

After the beam test the cavity stayed cold (4.2 K) in PETRA during regular high energy physics runs for 16 weeks. The superconducting cavity was detuned and unpowered at the fundamental mode frequency because the klystron power supply was used to drive NL-cavities. Every 2 weeks maximum E(acc) and Q_0 values were measured. After a total of 20 weeks in PETRA the properties of E(acc) = 2.5 MV/m and Q(residual) = 2.3×10^9 remained unchanged. The experiment was stopped due to a breakdown of the refrigerator.

d. KEK 1986 Beam Test

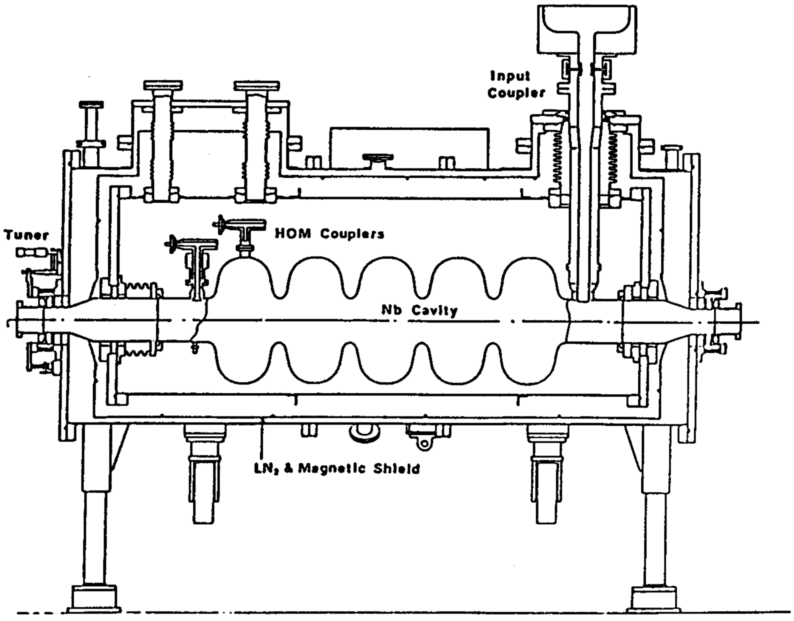


Fig. 14: Cross section of 1986 KEK beam test cryostat

As compared to the 3-cell KEK cavity (beam test in 1984) this resonator showed the following design changes:

- 5 cells (instead of 3 cells)
- RRR ca. 100 (instead of 60)
- input coupler is a coaxial antenna at beam pipe (see Fig. 15)
- higher order mode couplers are of coaxial antenna type, two are placed at beam pipe, two are placed at one end cell (see Fig. 16)

The high power input window is a coaxial disk at room temperature. This window as well as the complete inner conducter are cooled by water. Tuning of the cavity is done by a coarse and a fine mechanical tuner as well as by a piezo tuner. The cryostat has a length of 1.9 m and a diameter of 1.1 m. The static losses were measured to 13 W. A Permalloy cylinder at the radiation shield decreases the ambient earth magnetic field to 40 mG. The cryogenic system was the same as in the 1984 beam test.

During the beam test the following maximum values were reached:

E(acc) = 3.5 MV/m limited by field emission
I(beam) = 29 mA captured, limited by two high reflected cavity power
P(beam) = 13 mA accelerated, " " " " " " "

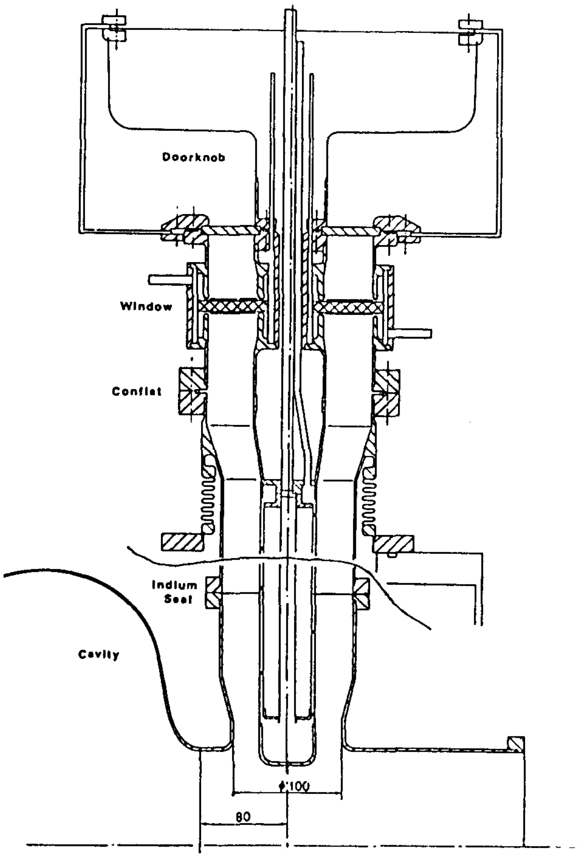


Fig. 15: KEK input coupler

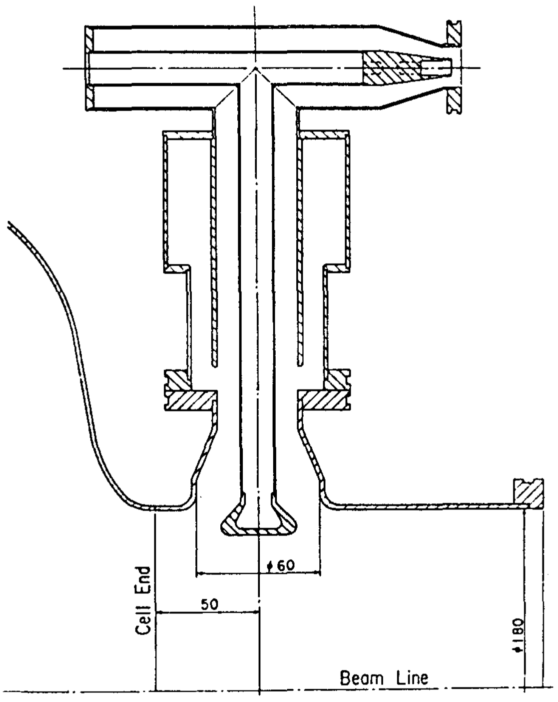


Fig. 16: KEK HOM-coaxial antenna

It turned out later that the excessive reflected power was caused by misstuning of the cavity voltage feedback loop. After the beam test the rf processing of the cavity was continued and a field of E_{acc} = 4.5 MV/m could be reached. Under those conditions the input coupler was loaded with 82 kW forward power (total reflective condition).

During the beam test a detailed study of longitudinal HOM-resonances was not done because high impedance longitudinal modes were outside the tuning capability (to be tuned on resonance). Transverse modes were tuned to resonances and a vertical betatron oscillation at twice the predicted current (3 mA) was observed.

Resonance frequency	508 MHz	
number of cells	5	
active length	1.5 m	
r/Q	600 Ohm	
E peak/E(acc)	1.97	
H peak/E(acc)	40.6 G/MV/m	
fundamental coupler	coaxial antenna	
Q(ext)	1.2×10^6	
window	coaxial disk at room temperature	
HOM-coupler	2 x coaxial antenna at beam pipe 2 x coaxial antenna at end cell	
typical damping of dominant modes	TM_{011}	6×10^3
	TM_{020}	3×10^4
	TE_{111}	8×10^4
	TM_{110}	4×10^5
	TM_{111}	1×10^4
tuning	mechanical coarse	
	mechanical fine	35 KHz
	piezo tuner	2.5 KHz
pressure dependence	72 Hz/mbar	
measured pressure fluctuation	1 mbar	
cryostat	diameter = 1.1 m L = 1.9 m	
static losses	13 W	
rf-losses	42 W at 3 MV/m	

Table 5 :Parameters of the KEK 5-cell cavity used in the 1986 beam test

e 1987 CERN SPS Beam Test

A 4-cell cavity with 358 MHz resonance frequency (LEP-design) was fabricated from RRR 100 Nb material. The cavity was equipped with HOM couplers according to the LEP conditions. In addition damping at the fundamental mode frequency was foreseen to lower the cavity impedance during the passage of the intense p-bunch of the SPS:

- active feedback (cavity at 4.2 K and superconducting)
- passive damping by a detuned input coupler line (cavity at room temperature but still in SPS).

The purpose of this beam test experiment is:

- to test a fully equipped LEP-cavity for a long period under operating conditions
- to accelerate $e^{+/-}$ and study the LEP injection
- to study the beam-cavity interaction

In previous tests the cavity showed an accelerating field of E(acc) = 7.3 MV/m. This cavity was installed in the SPS during August 1987 and the beam test is being carried out during the week of this workshop. Latest results: see H. Lengeler, this workshop.

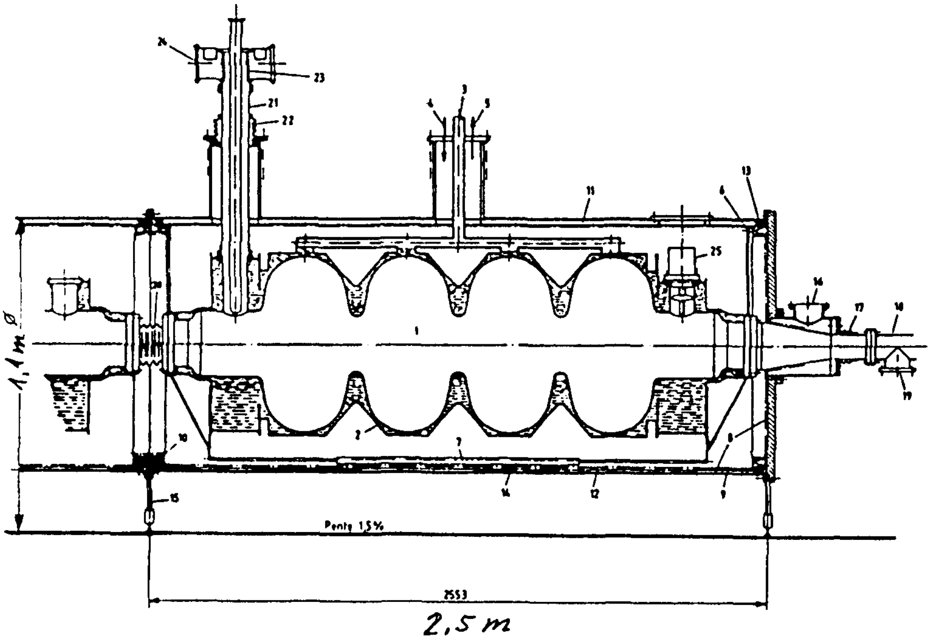


Fig. 17: Cross section of the CERN 1987 beam test cryostat

4. Résumé E(acc), V(acc)

Eight storage ring beam tests with superconducting cavities (f = 500 - 1500 MHz) have been carried out since 1982. The following limitations have been observed:

Limitation		Remarks
multipacting	2 x	solved by geometry
local heating, quench	3 x	better cleaning and welding use of higher RRR
field emission	2 x	dust?, complexity? general surface phenomena?
coupler heating	1 x	better design
vacuum failure	1 x	better design

An accelerating gradient of larger than 5 MV/m has been reached (only) once, the accelerating gradients demonstrated in a beam test are generally smaller (up to a factor of 2) as compared to laboratory test. Fig. 18 and Fig. 19 show the progress in time of E(acc) and V(acc). Although there is a tendency of increasing E(acc),the most progress is clearly gained in V(acc)), that is in the installed "superconducting" voltage. That means that the beam tested cavities became larger and more complex. Generally the time to prepare and process a beam test module is reported to be too short. Unforeseen difficulties and a fixed time window for the beam test force a non-optimal treatment of the cavities.

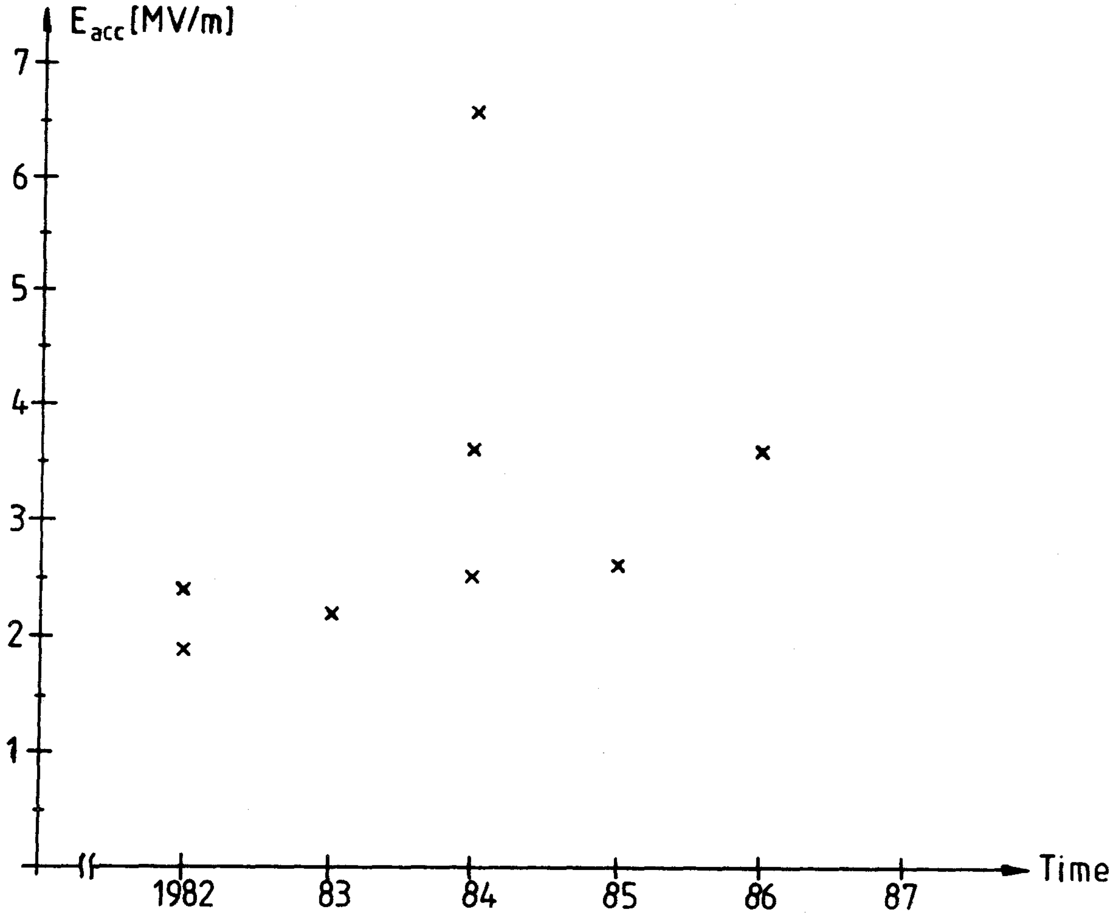


Fig. 18: Accelerating gradients measured in beam tests

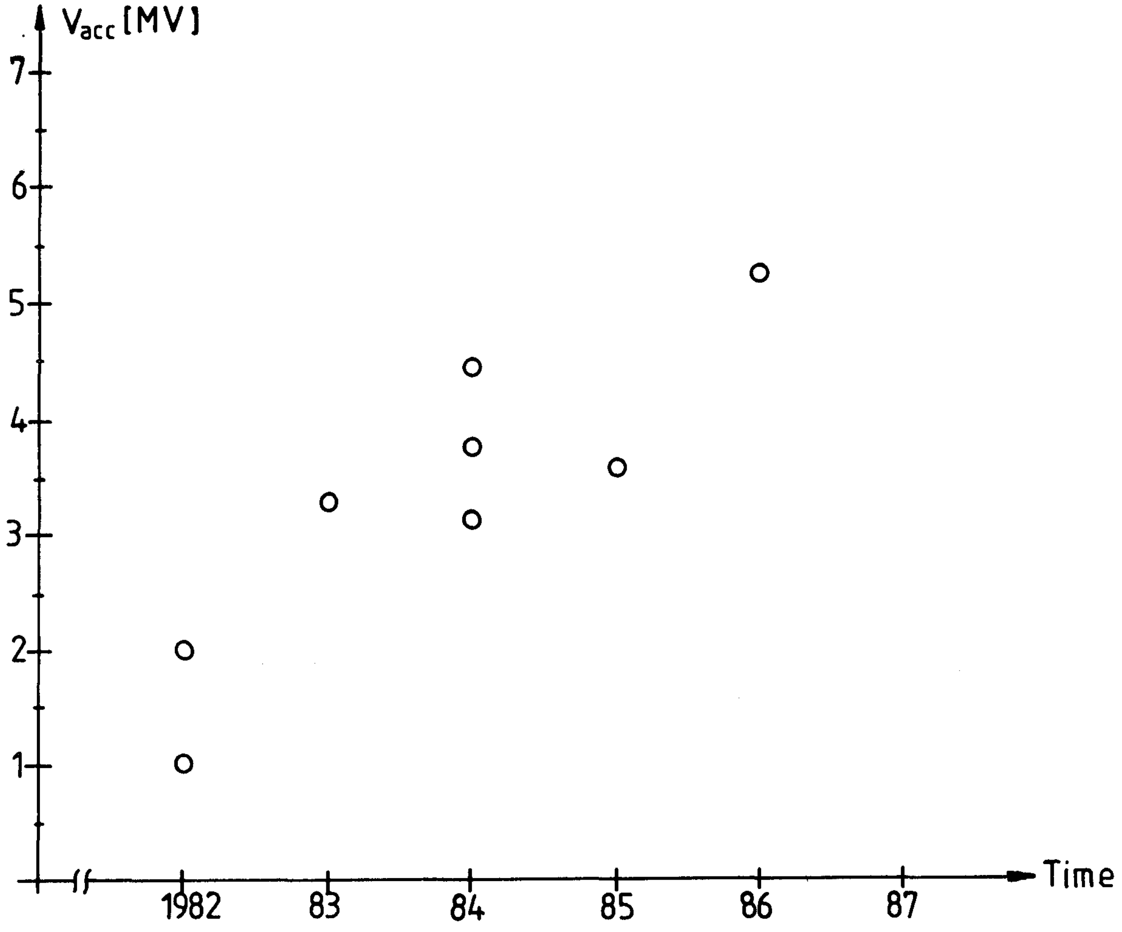


Fig. 19: Accelerating voltage produced in different beam tests

5. Résumé Input Coupler

Beam pipe couplers are generally adopted to couple the klystron power to the cavity. Rectangular waveguides are used at higher frequencies (CORNELL: 1500 MHz; DESY: 1000 MHz) whereas at lower frequencies coaxial lines are preferred (KEK, DESY: 500 MHz; CERN: 352 MHz). Transmitted rf power of 27 kW and reflected rf power of 80 kW are reported to work without problems. Simple joints (no choke joints) work with acceptable dissipation. Windows of different design are used. No brake of a high power window during operation with subsequent beam vacuum failure has been reported. Only in the early Karlsruhe test (1982) the window at 77 K became leaky but a second window at room temperature saved the beam vacuum. Nevertheless, a break of the input window is considered to be the most likely and also most dangerous accident. Experiments at Karlsruhe (13) and at Argonne (14) showed that in case of a beam vacuum failure all the LHe is evaporated within 20 sec. Because of these consequences the failure rate of input windows for normal conducting cavities would not be acceptable for a large superconducting rf-section.

The development of a high reliable input window section appropriate for high rf-power is an urgent demand. In the case of HERA and TMR the transferred beam power per input window is rather large. In Fig. 20 the maximum value for E(acc) vs. beam current is plotted. At 100 kW transferred power per input window the accelerating gradient is limited to values smaller than or slightly above 5 MV/m in case of HERA or TMR, respectively. This indicates the need of a input window for P(generator) > 100 kW.

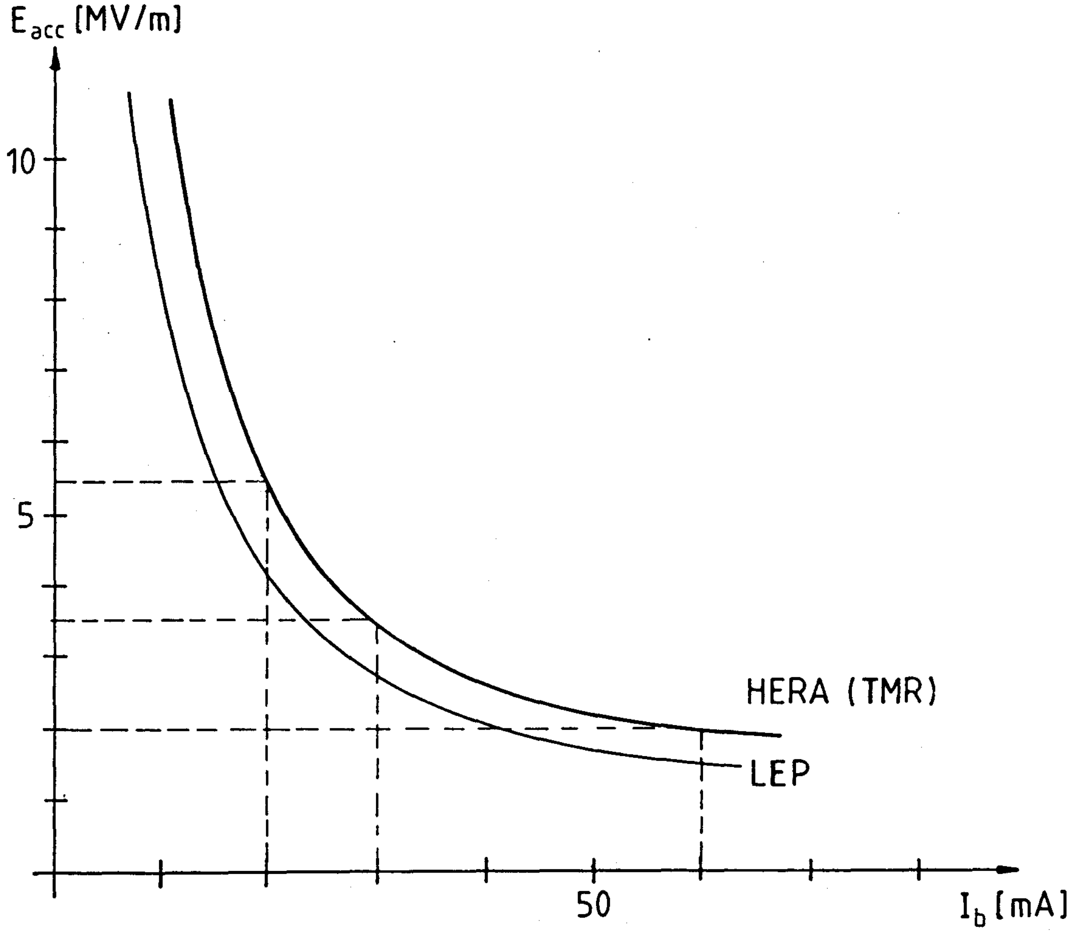


Fig. 20: E(acc) vs. I(beam) with 100 kW rf power per cavity (= per input window)

Input couplers with variable (or easily adjustable) coupling is another need for an effective use of superconducting cavities in storage rings (see Fig. 21). For a fixed generator power the cavity voltage depends strongly on the beam loading. At a given coupling value matched conditions can be reached for a certain beam current Io. For currents smaller than Io the cavity voltage increases with decreasing current which could be adjusted by decreasing the generator power. For current larger than Io, however, the cavity voltage drops to zero at twice the value of Io (see Fig. 21). To be prepared for a different beam current as originally designed or to match the natural decay of the beam current between storage ring

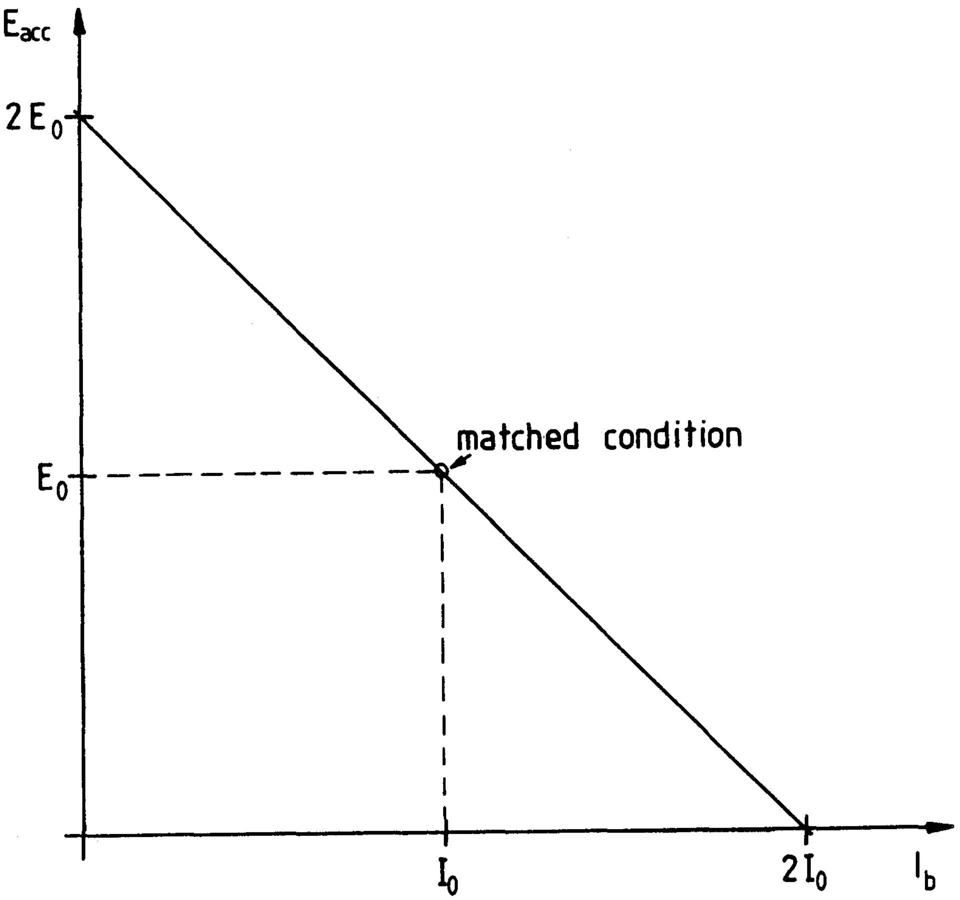


Fig. 21: E(acc) vs I(beam) with constant input coupling and constant generator power

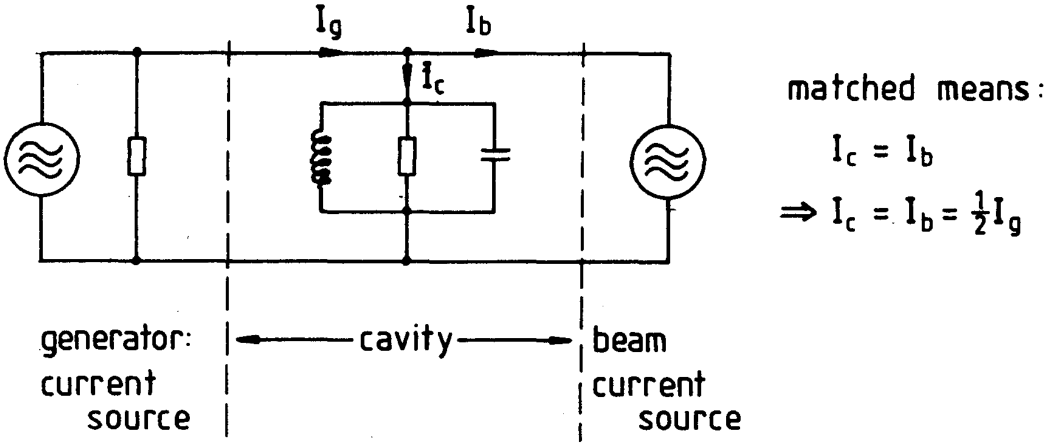


Fig. 22: Lumped circuit equivalent of beam loaded cavity

filling cycles, a variable coupler is needed. The CORNELL input coupler was squeezed at the long side of the rectangular waveguide (Niob at 2.3 K) to change the coupling to the cavity. At Desy an adjustable transformer is used in the rectangular waveguide beyond the coaxial window and outside the cryostat. The coupling can be changed in the range 0.1 to 10 according to the standing wave pattern in the window section (1987 beam test).

6. Résumé HOM coupler

Beam pipe couplers with coaxial antennas or loops at lower frequencies (CERN, DESY, KEK) or waveguide couplers at higher frequencies (CORNELL, DESY) are generally adopted. Dominant HOM-modes (i.e. those, who have high values of R/Q) in superconducting cavities are equal or even stronger loaded as those HOM modes in a pure Cu-cavity.

In beam experiments individual HOM-modes behave as predicted by bench measurements or by calculations. The measured integral HOM power extracted by HOM couplers is smaller, however, in most cases as compared to TBCI calculations. This is explained by not measured power radiating into beam line or into fundamental coupler line.

Instability thresholds have been observed by tuning distinct dipole modes to resonance. On a statistic basis, however, all HOM-impedances have to be summed up. The drive term of a certain multiturn instability results as the difference of all HOM impedances at two distinct frequencies (according to the mode of instability) incremented by the revolution frequency. The result of this calculation is a probability function of the onset of instability vs. beam current. These calculations have been compared carefully with measurements during the 1984 CORNELL beam test (see Fig. 8) and agreed within a factor of two.

It should be mentioned that the instability probability has a different interpretation for superconducting as compared to normal conducting cavities. Normalconducting cavities change their HOM-spectrum during operation: increased heating with increased field level, changed temperature of cooling water and changed ambient temperature result in changes of dimension. As result a storage ring might change from stable to unstable condition (or vice versa). In this sense, the instability probability for normalconducting cavities predicts the stable or unstable operating condition of a storage ring over a long time. In the case of superconducting cavities, however, the working conditions at cryogenic temperatures are rather stable. As consequence the stable or unstable operating condition will be preserved over a longer time. Only permanent detuning of the dangerous mode will change this condition. In this sense, the instability probability for superconducting cavities predicts stable or unstable operating conditions of a storage ring for different sets of produced cavities.

All reported experiments show no evidence of so called "trapped modes". These modes concentrate the stored energy in the middle cells (or around the middle irises) so that it would be difficult to damp them by beam pipe couplers.

7. Résumé cryostat

Horizontal LHe-bath cryostats are used for beam tests. Different techniques are applied to close the inner LHe-vessel: Indium joints, brased or welded connections. The standby losses range from 3 W/m to 6 W/m. These numbers are high as compared to typically 0.5 W/m for superconducting magnets.

Considerable safety problems exist at DESY and KEK applying the rules of the high pressure vessel index. This situation was described by Y. Kojima, KEK: "According to the rules Niobium at 4.2 K does not exist." The lack of mechanical data of Niobium at cryogenic temperatures is not only a problem of "legal safety". These data are a need for cryostat engineering under safety aspects ("real safety") and more attention has to be payed to this field.

Superconducting magnets can withstand pressure up to 15 bar because of their tubular construction. Superconducting cavities might collapse above 3 bar. This results in big vent-lines and low pressure safety valves. One way out of these problems is the consequent application of pipe cooling to superconducting cavities.

8. Résumé long time experience

Two cavities stayed longer in the storage ring than the usual 1 to 2 weeks of test procedure. The 1983 CERN cavity remained 8 weeks in PETRA after the beam test. The cavity was kept at 4.2 K but was detuned and unpowered. After this period the accelerating gradient of 2.1 MV/m was unchanged, the Q value dropped from 1.7×10^9 to 0.6×10^9.

The 1985 Desy 9 cell cavity stayed 16 weeks in PETRA after the beam test. This resonator was kept at 4.2 K and was unpowered, too. Every two weeks the maximum accelerating gradient of 2.5 MV/m and the Q value were measured. The gradient and the residual Q of 2.3×10^9 stayed constant over the whole period.

The second experiment proves that the degradation of Q as observed in the first experiment is not a typical consequence for a cold cavity in a storage ring. It should be noted, however, that both cavities stayed in this ring under non operating conditions. In both cases the klystron power was needed to supply normalconducting cavities. Furthermore the control of such a complex experiment would have absorbed too much manpower. A simple cavity (single cell ?) with diagnostic and automatic control would be an interesting experiment to gain more information about long time degradation effects.

9. Final Remarks

Planning, preparation and performing a storage ring beam test needs a great deal of time and manpower. So the question is allowed, why to carry out a beam test at all. Several answers are usually given:

- Demonstration of max E(acc)

The value of max E(acc) as seen by the beam is considered to be the most important output of a storage ring test. These values are usually smaller as those obtained in laboratory tests. But here two experiments of quite different complexity are compared. A beam test SRF-module has to be completed in every aspect (high input power line, cryogenics, controls, interlocks e.t.c.) whereas in a laboratory test a lot of accessories are missing. A complete SRF-modul can be tested outside the beam and can demonstrate the maximum accelerating gradient as well.

- Check of instability behaviour

The beam-cavity interaction is well understood. Predictions by careful bead-pull measurements and code calculations are verified by beam experiments, so far. A newly developed HOM-coupler scheme should be tested by beam exitation, of course. But this can be done at any value of E(acc).

- Check of high power input coupler

The high power behaviour of the input line can be tested outside the ring under total reflective conditions or with two couplers cascaded under matched conditions.

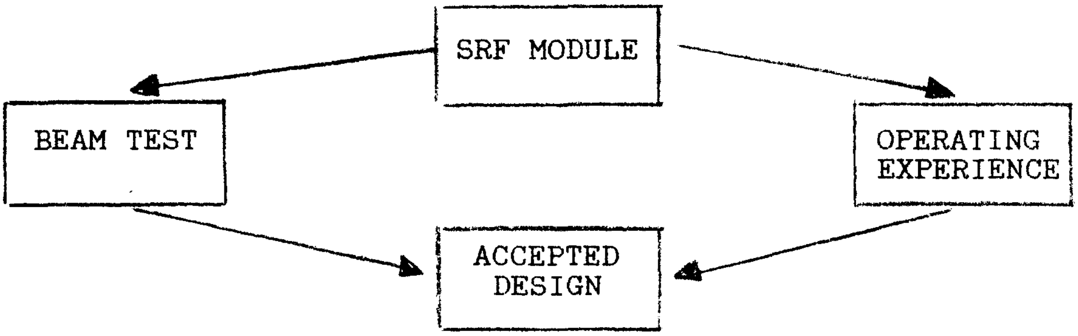
- Get operating experience

This also can be done outside the ring with a completed SRF-module.

- Long time contamination effects

A possible contamination of a SRF module in a storage ring has not been investigated over a long enough period of time under operating conditions. Usually a beam experiment is much too short to get valuable data.

All beam tests have been prepared under heavy time pressure. Usually it is the beam test itself, when the complete system works together for the first time. More operating experience is urgently needed and can be gained outside the storage ring. This experience together with the results of a storage ring beam test are needed to make a SRF-model to an accepted design.



Acknowledgement

The author wishes to thank H. Lengeler, S. Noguchi, H. Padamsee, R. Sundelin and W. Weingarten for kindly supplying information for this paper.

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