BEAM TESTS AND OPERATION OF SUPERCONDUCTING CAVITIES

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1. Overview

Beam tests and operation of superconducting cavities conducted since the third workshop on RF superconductivity (Argonne, Sep.1987) are reported in this paper. This paper is concerned with electron machines.

Beam tests and operation of superconducting cavities performed in electron machines so far are summarized in Table 1 in chronological order. The beam tests up to 1983 were reviewed by Dr. Sundelin[1] at the second workshop and the beam tests up to 1986 were reviewed by Dr. Proch[2] at the third workshop.

Table 1 Overview of the beam tests and operation of sc cavities

Year	Laboratory	Ring	Cells	f(MHz)
1982	Cornell	CESR	2 x 5	1500
1982	Karlsruhe	PETRA	1	500
1983	CERN	PETRA	5	500
1984	KEK	T-AR	3	508
1984	Cornell	CESR	2 x 5	1500
1985	DESY	PETRA	9	1000
1986	KEK	T-AR	5	508
1987-89	CERN	SPS	4	352
1987	DESY	PETRA	2 x 4	500
1987-89	Darmstadt	S-DALINAC	5+ 8x20	2997
1987-88	KEK	T-AR	2 x 5	508
1988-89	KEK	T-MR	16 x 5	508
1989?	DESY	PETRA	2 x 4	500
1989?	CEBAF	Injector	2 x 5	1497

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Since July 1987 LEP prototype 352 MHz 4-cell cavity has been tested in CERN-SPS[3,4,5]. During the last two years, the cavity has undergone 20 cooldowns and long-term performance of the cavity has been investigated. In Oct. and Nov. 1987, DESY 500 MHz two 4-cell cavities were tested in PETRA to demonstrate the feasibility of application to HERA[6,7]. The first beam test of Wuppertal 2997 MHz cavity in the Darmstadt Superconducting Linac (S-DALINAC) was conducted in Aug. 1987. The superconducting injector has been operated for experimental use and the superconducting main linac of recyclotron has been tested[8]. Beam tests of KEK 508 MHz two 5-cell cavities were conducted in TRISTAN-AR (T-AR) three times, Oct. and Nov. 1987 and Mar. 1988, to confirm the feasibility of operation in TRISTAN-MR (T-MR). Sixteen 508 MHz 5-cell cavities were installed in T-MR at KEK in 1988 and have been operated for electron-positron colliding beam experiment more than six months[9,10,11]. Some parameters of the cavities, the input couplers and the HOM couplers in these beam tests and operation are summarized in Table 2.

Table 2 Parameters of the beam tests and operation since the third workshop

Laboratory	CERN	DESY	Darmstadt	KEK	KEK
Ring	SPS	PETRA	S-DALINAC	T-AR	T-MR
Period	Jul'87	Oct/Nov'87	Aug'87	Oct/Nov'87	Nov'88
	-89 (cont)		-89 (cont)	Mar'88	-89 (cont)
Cells	4	2 x 4	5 + 8 x 20	2 x 5	16 x 5
f (MHz)	352	500	2997	508	508
R/Q (ohm)	232			600	600
RRR	156		30-100	150	100-170
Input cpl.	Coaxial	Coaxial	Coaxial	Coaxial	Coaxial
Window	Ceramic	Ceramic	Ceramic	Ceramic	Ceramic
Type	cylindric	cylindric	disk	disk	disk
Qext	$8x10^5$	$2x10^5$	$3x10^7$	$1-1.4x10^6$	$0.8-1.2x10^6$
HOM cpl.	Coaxial	Coaxial		Coaxial	Coaxial
Type		two stub			
/cav	2	3	no	4	2

Future beam tests and operations include following plans. DESY 500 MHz two 4-cell cavities will be tested in PETRA with the aim of storing maximum current in PETRA (up to 60 mA) in HERA condition[7]. In T-MR at KEK, other sixteen cavities will be added in fall 1989 and in total 32 cavities will start to be operated to raise the energy of T-MR to more than 32 GeV. At CEBAF, construction of the 5-pass recirculating linac using 338 superconducting 5-cell cavities at 1497 MHz is scheduled for completion in 1994. The injector with two 5-cell superconducting cavities is to be operated to produce a 5 MeV beam in fall 1989[12]. At CERN, the upgrade of LEP energy using superconducting cavities is under way. The first four Nb cavities will be installed in LEP[13].

2. Storage and Acceleration of the Beam

In the CERN test in SPS, the positron beam of 0.28 mA was accelerated using the new Standing Wave Cavities on one of the lepton cycles, with the SPS operating in the interleaved mode. The accelerating field of the 4-cell superconducting cavity was kept few hundred kV during the injection; the field in the cavity was rapidly (100ms) pushed up to 5.5 MV/m towards the end of the lepton cycles.

During the acceleration of high intensity proton beam, damping of the cavity impedance at the fundamental mode frequency is needed. The RF feedback to compensate for beam loading is used to reduce the impedance to 200 kilo ohm. Another method with a resonant line connected to the main coupler to damp passively has been tested[3].

In the DESY test in PETRA, the electron beam acceleration test was conducted. Because of high designed current of 60 mA for HERA condition, power rating of the input window and strong damping of HOM's are quite essential items. A "three plug tuner" input transformer is used in the waveguide just before the input window. The effective coupling can be adjusted in the range of 0.2-5.0. In the beam test, the input coupler and the input transformer worked up to 200 kW equivalent power. The maximum stored current was 4.4 mA, which was limited by instabilities in 16 detuned normal conducting cavities. A new beam test in PETRA is planned for 1989 to store maximum current in PETRA (up to 60 mA); normal conducting cavities that would limit the current up to 5 mA will be by-passed so that the beam only sees the superconducting cavities[7].

The superconducting injector at Darmstadt, containing a 5-cell and two 20-cell cavities, have been used to provide electron beam for two experiments after the first beam test conducted in Aug. 1987. One is the channeling radiation experiment, which requires low currents (1nA) but the best beam quality. Measurements show that there is no significant beam divergence. The other is the nuclear resonance fluorescence experiment, which requires high currents and long running time. The superconducting injector has produced electron beam with energies of 2.5-8 MeV for these experiments successfully for more than 900 hours. Six 20-cell cavities out of eight have been installed and tested in the main linac. The electron beam has been taken back in the beamline of the first recirculation. Although two cavities with RRR of 100 reach the accelerating field of 5-6 MV/m, the rest cavities show relatively low field of 1-3 MV/m. The lower field is considered to be due to the lower value of RRR of 30, those cavities being fabricated from reactor grade niobium. Two cavities with the lowest accelerating fields will be replaced by cavities fabricated from the high purity niobium[8].

In the KEK beam tests in T-AR, the electron beam was accelerated and the maximum values obtained were;

a) 69 mA of e^- beam was stored at 2.5 GeV by one 5-cell (2MV/m)

b) 21 mA of e^- beam was accelerated to 6.5 GeV by 2 x 5-cell (5MV/m)

c) 10 mA of e^- beam was accelerated to 8.0 GeV by 2 x 5-cell (5MV/m) + normal conducting cavities

d) power transfered to the beam was 86 kW/5-cell

The maximum stored current was studied in detail with respect to Robinson stability, that will be discussed in a later section.

An outline of KEK-T-MR operation since the installation of the sixteen cavities in 1988 is shown in Table 3 and in Fig.1(a). After the first cooldown of 16 cavities, the electron positron colliding beam experiment, the physics run, started in Dec 1988. The total accumulated time of the cavities at 4.4 K amounts to 5000 hours; 3100 hours have been provided for the physics run. So far the beam current is limited to 11 mA by a trouble of two N type connectors of HOM couplers and not by any instability. The operation of the superconducting cavities in the physics run has been performed stably. Some experiences obtained during the long-term operation will be mentioned in a later section.

Table 3 Outline of TRISTAN-MR operation at KEK

Beam Energy	30.7 GeV
Beam Current	10 mA (e^- x 2 + e^+ x 2) bunches
Number of cavities	104 x 9 cell(normal conducting)
	16 x 5 cell (superconducting)
Accelerating voltage	320 MV (normal conducting)
	105 MV (superconducting)
Eacc at operation (super)	3.5 MV/m - 6.0 MV/m
average of 16 cavities	4.4 MV/m
Power transfered to beam	40 - 70 kW/5cell

3. Long-term performance of the cavity in the ring

Long-term performance of the cavity under a real accelerator condition is a quite significant problem. Eacc(max) and Q-value are important criteria to estimate the cavity performance. It is one of important questions that whether the cavities keep high Eacc(max) and Q-value in a real accelerator for a long period of time. Environmental conditions such as vacuum condition and radiation are also essential factors related to the long-term performance.

3-a) Eacc(max) and Q-value

Long-term performance of the cavity has been investigated at CERN and KEK. The CERN cavity has undergone 20 cooldowns and the total accumulated time of the cavity at 4.5 K is 6500 hours in SPS. Eacc(max) remained unchanged within the test interval and was 7.1 MV/m, that indicates no degradation from the laboratory test. The Q-value, on the other hand, shows a large scatter. Most of the observations show Q-value of 2-3x10^9. On several occasions, however, Q-values of less than 1x10^9 were observed. The lower values of Q are explained as; although the static homogeneous component of the ambient magnetic field is compensated by coils fixed at the vacuum tank, supplementary magnetic fields generated during operation may be trapped during cooldown or

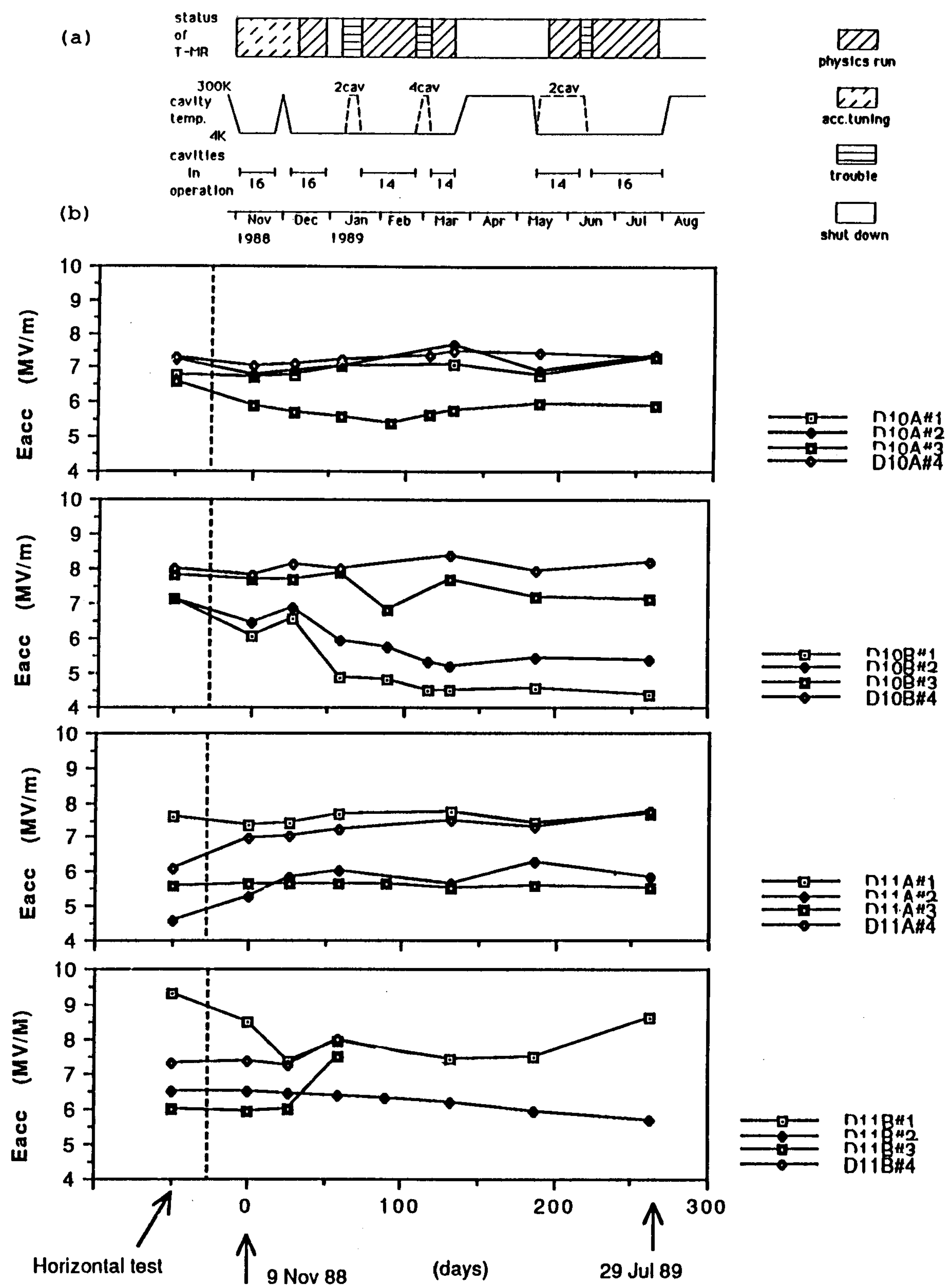

Fig.1 (a) describes the outline of T-MR operation at KEK. It includes the status of the T-MR accelerator, the temperature of the cavities and numbers of operated cavities. (b) gives long-term performance of the sixteen cavities showing Eacc(max).

quench recovery. The lower Q-value was restored to 2.8×10^9 by warming up the cavity and cooling down in a small ambient magnetic field. It can be concluded that the Q-value remained essentially unchanged[5].

In the KEK operation in T-MR, 16 cavities have been operated during the last nine months. The total accumulated time of the cavities at 4.4 K amounts to 5000 hours, in which, 3100 hours are occupied with the physics run with beams of typically 10 mA. Before installed in T-MR, the cavities had been tested in the vertical cryostat and in the horizontal cryostat. Fig. 2 and Fig. 3 show the Eacc(max) and the Q-value, respectively, measured in the vertical tests and in the horizontal tests. The Eacc(max) of some cavities in the horizontal test was degraded by 20-30 % compared with that in the vertical test. As for the Q-value, although a large error of nearly 20 % due to the method of measuring liquid He consumption should be considered, some degradation is seen in the horizontal test. This degradation is considered to be due to dust contamination during the assembly of cavities, couplers and other components in the horizontal cryostats. As long as the long-term performance in the real accelerator is concerned, the Eacc(max) and Q-value measured in the accelerator should be compared with those in the horizontal tests, not with those in the vertical tests. Fig.1(b) shows a change of Eacc(max) of each cavity since the first cooldown in T-MR up to now comparing with data in the horizontal test. Fourteen cavities out of sixteen have shown no degradation. These cavities have been operated stably with the field of 4.0-6.0 MV/m. Two cavities (D10B#1,D10B#2), which are located in the same cryostat, however, showed degradation of Eacc(max) after one week operation of the physics run. Table 4 shows Q-value measured in the horizontal tests and in T-MR. Q-values of these two cavities also reduced to 0.6×10^9 and 1.1×10^9, respectively, although those of other cavities show no clear degradation. Electron loading measured through the monitor port and X-ray measured near the cryostat show strong field emission in these two cavities. The degradation of these two cavities is considered to be caused by dust accidentally from somewhere.

<u>3-b) Environmental Conditions</u>

Vacuum pressure in operational condition is typically $1\text{-}3\times10^{-10}$ mbar in SPS and $3\text{-}20\times10^{-10}$ mbar in T-MR. In the CERN beam test the accelerator vacuum conditions were estimated in view of the large

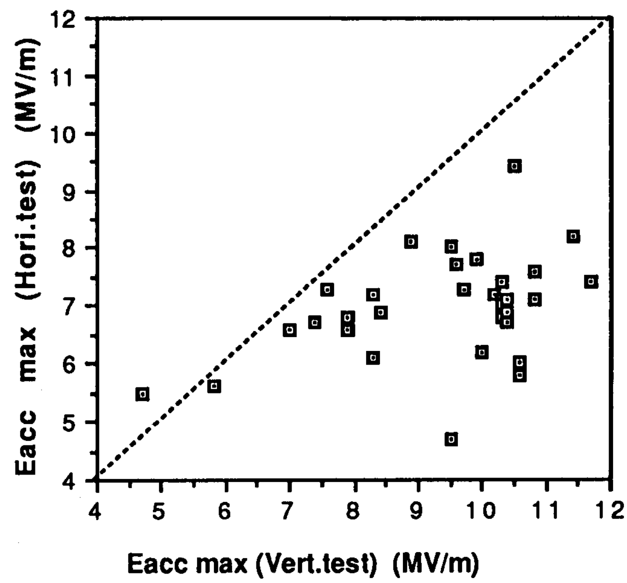

Fig.2 Eacc(max) of 32 cavities measured in vertical tests and in horizontal tests at KEK.

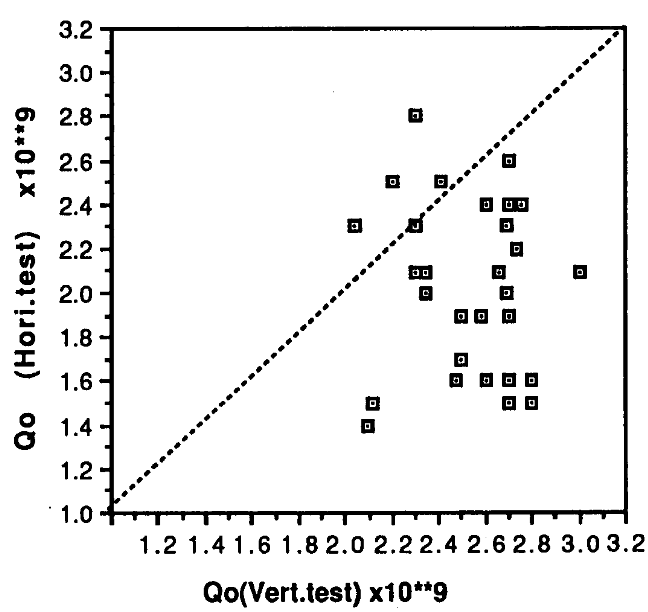

Fig.3 Q value of 32 cavities measured in vertical tests and in horizontal tests at KEK.

pumping speed of the superconducting cavity surface. The total amount of the absorbed gas after two months operation was estimated to be 0.34 mbarl, calculated by vacuum pressure and pumping speed of the ion pumps. Independent method measuring the desorbed gas on the occasion of warming up confirmed the above result. A companion experiment conducted in CERN showed that between one and five monolayers equivalent gas exposure the high field Q-values were lowered by electron loading. Based on this result, CERN foresees that the cavity can most likely be kept at 4.5 K without degradation for a period of 3 years[5].

Also at KEK in T-MR the desorbed gas was measured. The result is 3 mbarl after two months operation, that is 10 times larger than that of SPS. The absorbed gas during two months corresponds to two monolayers in T-MR[14]. For the present no degradaion of Eacc(max) and Q-value was measured except for the two cavities. In usual operational sequence the cavities are warmed up after every two or three months operation. This seems to contribute to keeping good performance of the cavities.

Table 4. Q value measured in the horizontal tests and in T-MR at KEK

Cavity No.	Q-value ($\times10^9$) at Eacc (MV/m)		
	Horizontal test	T-MR 20 Mar.'89	T-MR 19 Jul.'89
D10A#1	1.6 (6.6)	2.4 (5.5)	2.2 (5.5)
D10A#2	2.1 (6.5)	2.0 (6.0)	2.2 (6.0)
D10A#3	-	1.4 (5.0)	1.3 (5.0)
D10A#4	1.9 (6.3)	1.9 (6.0)	1.9 (6.0)
D10B#1	1.7 (7.0)	0.78 (4.0)	0.58 (4.0)
D10B#2	1.6 (6.0)	1.2 (4.5)	1.1 (4.4)
D10B#3	2.8 (6.8)	2.7 (6.0)	2.2 (6.0)
D10B#4	2.4 (7.0)	2.8 (6.0)	2.5 (6.0)
D11A#1	2.3 (6.9)	2.7 (6.0)	2.2 (6.0)
D11A#2	1.5 (4.2)	1.5 (5.0)	1.5 (5.0)
D11A#3	2.4 (5.4)	2.6 (5.0)	2.1 (5.0)
D11A#4	1.4 (5.9)	2.5 (6.0)	2.1 (6.0)
D11B#1	2.1 (8.0)	2.6 (6.0)	2.2 (6.0)
D11B#2	1.9 (5.5)	1.7 (5.5)	1.4 (5.5)

3-c) Operational Experience in T-MR

Problems encountered during the last nine months operation in T-MR are described[15]. The most serious problem was vacuum leak at the ceramic window of the input coupler. One coupler (#6b) developed a vacuum leak during cavity aging operation after a short shut down of the accelerator. There was a visible crack at the ceramic window. After warming up the cavity and changing the input coupler, we tried to operate the cavity again. It turned out, however, not only the cavity whose coupler developed the leak, but also the next cavity (#6a) in the same cryostat were contaminated too much to be powered. The two cavities were cooled down again, detuned and unpowered until they were changed by #13a#13b in the next shut down.

Another input coupler (#3b) developed a vacuum leak during the physics run. The coupler was changed by another one and could be operated again. A leak without visible crack was at the ceramic window.

Unexpected amount of fundamental rf (1kW) came out of the HOM couplers on some occasions due to breakdown of HOM couplers which changed the filter frequency for the fundamental mode. Some N type connectors at the end of HOM output cables in vacuum tank were burned. This trouble has limited the beam current to 11 mA. An interlock system is now equipped to detect the breakdown of HOM couplers measuring the fundamental power from the HOM couplers.

4. RF Controllability

Some characteristic features of the superconducting cavities have to be taken into consideration when we design and construct the RF system.

4-a) Robinson Stability

Since the beam-induced voltage is large in superconducting cavities due to the high impedance, the stored current will be limited by Robinson instability[16]. The Robinson stability limit is represented as[17]

$$I = \frac{2V_c \sin\phi}{\sin(2\phi - 2\alpha)} \times \frac{1}{(\frac{R}{Q}) \times Q_L} \quad (1)$$

where ϕ is the synchronous angle, α is the tuning angle offset, Vc is the cavity voltage and Q_L is loaded Q. It can be seen from Eq.(1) that

(i) at injection energy (ϕ=60-80 deg), shifting the tuning angle offset by several ten degrees is quite effective to increase the maximum stored current and that (ii) at the maximum energy (ϕ=45 deg), shifting the tuning angle offset is not very effective.

In the KEK beam test in T-AR, the maximum stored current was studied in detail with respect to Robinson stability. The electron beam was stored by one 5-cell superconducting cavity, while the other 5-cell and normal conducting cavities were detuned. The maximum stored current was measured at the injection energy of 2.5 GeV changing the cavity field and cavity tuning angle offset. The result is shown in Fig.4. It was confirmed that (i) the maximum stored current is in agreement with Robinson stability limit and that (ii) shifting the tuning angle offset is quite effective at the injection energy.

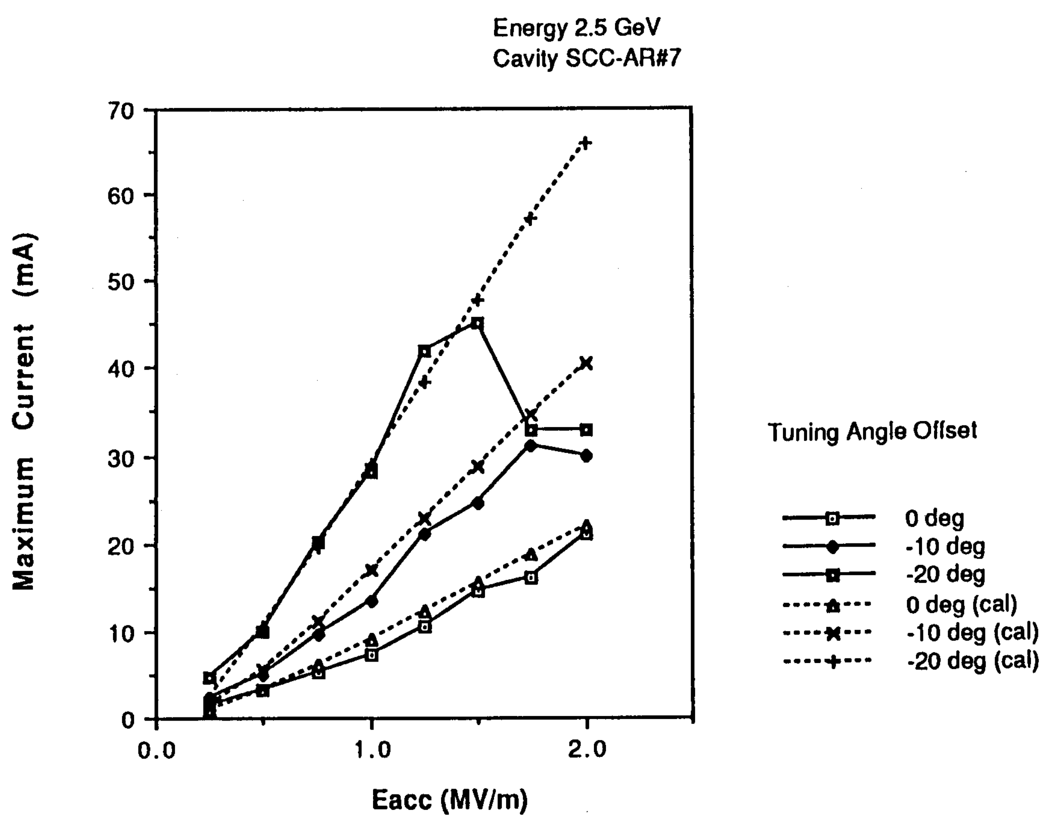

Fig.4 Maximum stored current in T-AR beam test. Solid lines indicate measured values; dashed lines indicate calculated values from Robinson stability limit.

In case of T-MR operation, the Robinson stability is severer restriction at injection energy because of lower accelerating field than at the maximum energy. The Robinson stability limit was calculated at the injection energy. The stability limit depends on accelerating voltage of the cavities and on a total amount of ring impedance. Provided that the impedance is 8000 mega ohm and the field in the superconducting cavities is 1.0 MV/m at injection energy, the calculation shows that 20 degrees of detuning is necessary to store 16 mA. Taking a transient effect into consideration, the tuning angle is shifted by 30 degrees at the injection in T-MR. At the maximum energy, however, such a heavy detuning is not needed and even causes an excess klystron power. Consequently the tuning angle offset is operated in a programmed pattern, shifted by 30 degrees at the injection and restored to 5 degrees at the maximum energy[11].

4-b) Cavity Tuning Loop

The cavity tuning system is summarized in Table 5. The CERN cavity uses Ni-bars supporting the cavity for the tuning. Fast movement is achieved by magnetostriction and slow movement is by temperature change of the same Ni-bars. The Darmstadt cavity and the KEK cavity use a stepping motor for coarse tuning and a piezoelectric transducer for fine tuning. The tuning system of KEK is located at the end plate outside the cryostat, whereas that of Darmstadt is located in the helium tank. The DESY cavity needs only slow tuning system using a stepping motor because the bandwidth is relatively wide.

Mechanical oscillations have been observed in the superconducting structures. The KEK cavity has a mechnical resonance at 40-50 Hz. Similar oscillations are observed in the Darmstadt cavity in the frequency range of 200-400 Hz and in the CERN cavity in the frequency range of 50-100 Hz. These oscillations restrict the band of fast tuning feedback control loop to very low frequency. The band of the piezoelectric transducer of the KEK cavity is limited up to 20 Hz. The phase oscillation caused by the mechanical oscillation is typically +-3 degrees in the KEK cavity. But this is not a serious problem because the phase and amplitude of the cavity field are stabilized by other fast feedback loops to control the cavity field.

Table 5 Cavity tuning system

	CERN	DESY	Darmstadt	KEK
frequency	353 MHz	500 MHz	2997 MHz	508 MHz
bandwidth	440 Hz	2500 Hz		500 Hz
coarse tuning	Ni bar	Motor	Motor	Motor
(method)	temperature			
(stroke)	50 kHz		1 MHz	400 kHz
fine tuning	Ni bar	none	Piezo	Piezo
(method)	magnetostrict			
(stroke)	1.5 kHz			6 kHz

The phase lock loop and the amplitude control loop for the cavity field have confronted no major problems. The phase variation less than +-0.3 degrees is easy to be achieved.

Some troubles have taken place in the cavity tuning system. At Darmstadt the performance of the piezoelectric transducers degraded in helium atmosphere at 2 K and some of the mechanical coarse tuners become inoperational after cooldown. They have started to test another type of tuner using magnetostrictive devices. At KEK the tuning system is located in the room temperature. The stroke of the piezoelectric tuning is large enough. One problem was that one of the piezoelectric transducers failed after nine months operation caused by radiation damage.

4-c) Quench Detection and Interlocks

When a quench occurs, a large amount of liquid helium is consumed. In order to prevent helium pressure rise and keep stable operation of the refrigerator, fast detection of the quench is necessary. Possible mothods are; detecting the helium pressure rise, temperature measurement and RF measurement. To detect the quench fast enough, the temperature measurement or the RF measurement is preferable.

At CERN a quench is detected by excessive difference between incident and reflected RF power. If a quench is detected, the RF is switched off but the RF feedback to compensate for beam loading is not switched off. In the DESY cavity test, a quench is detected by 60 carbon resistors with a fast data logging system. The sensitivity is 0.5 mK at 4.2 K. In the cornell beam test in 1982 in CESR, ratio of energy in the cavity to incident power was interlocked. In the T-MR operation at KEK, a quench is detected from a decrease of the cavity field and/or time gradient of the cavity field. The result is that a quench is detected within 20 msec and the pressure increase is below 1 mbar.

Once the quench occurs, there might be a choice whether the beam should be dumped or not. In case of using the cavities in an accelerator for experimental use, it is desirable not to dump the beam. Consequently the cavity should be detuned immediately after the quench occurs to avoid a large amount of power consumption caused by the beam-induced field. In the T-MR operation at KEK, when a quench is detected the klystron rf is switched off and the cavity is detuned away by 2-3 kHz without the beam dumped.

All interlocks equipped for the superconducting cavities in the T-MR operation at KEK are divided into two groups; one is to switch off one klystron and the other is to switch off all klystrons so that the beam is dumped.

(1) switch off one klystron;

cavity; quench detectors, vacuum (CCG), HOM fundamental power,
arcing of input couplers, temperature of input couplers,
maximum allowable cavity field, etc

cryostat; helium level, heater ready,

wave guide; reflections, flow switches, thermo switches

(2) beam dump

temperature rise of HOM cables

helium pressure rise

4-d) Recovery Procedure

If a lot of cavities are used in operation, it is almost impossible that all cavities work without any troubles. On some occasions an interlock works to switch off the RF, by cavity troubles such as a quench, vacuum trouble and arcing, or by troubles in klystron or in power supply system, etc. When the cavities are in operation in an accelerator providing beams for experimental use, the following conditions are quite necessary to keep stable operation. (i) To store the beam stably even if one (or more) klystron is switched off by some interlock and (ii) to switch on the RF after the trouble is solved, under the condition of the beam circulating. In the present stage, four klystrons are used for superconducting cavities in T-MR, each klystron driving four cavities. In usual operational condition in T-MR, the stored beam is not lost when one klystron is switched off. The latter condition should be treated carefully because of high beam induced voltage in the superconducting cavities.

In the T-MR operation at KEK, the sequence of the switching on the RF is done in the following way. The sequence of RF switching-on is divided into two stages. First, when the RF is switched on, the phase lock loop (PLL) and the automatic level control loop (ALC) to stabilize the klystron output are closed. The stepping motor starts to move searching a tuning point. The generator voltage (Vgr) is established so that the amplitude is dependent on beam current and energy and the phase of the Vgr is adjusted to appropriate position. Second, all of four cavities are tuned, then the ALC and PLL to control the cavity field are closed. The reference voltage of the ALC is raised to normal operation voltage. The responce speed of the tuning loop is 20 msec, 10 times slower than the speed of the PLL and ALC, restricted by the mechanical resonance. At the time the feedback loop is changed from the klystron control to the cavity field control, there is a possibility for the feedback loop to diverge. In this transient, the cavity field feedback loop should be changed smoothly enough so that the tuning loop could catch up with the change in the tuning angle. For that purpose the loop gain of the feedback loop is raised gradually after the loop is closed[11].

4-e) Field Calibration and Phase Adjustment

Calibration of the amplitude of the cavity field has been in general based on Q ext of the monitor port and cable attenuation from the monitor port to rf detector. Independent check was done from synchrotron frequency of the stored beam (KEK) or from the beam energy (CERN). These were in good agreement within 5%.

In T-MR operation, the phase of the cavity field was adjusted taking advantage of the high beam-induced voltage in superconducting cavities. If the tuning angle offset is set to zero, the cavity field (Vc) becomes

$$Vc = \{4(R/Q) \times Q_L \times Pg\}^{1/2} - I_b \times (R/Q) \times Q_L \times \cos(A) \qquad (2)$$

where, I_b is the beam current, Q_L is the loaded Q, A is the synchronous angle, and Pg is the generator power. The high impedance of the superconducting cavity makes the second term comparable to the first term. The phase of the superconducting cavities was adjusted as follows. The beam was stored by normal conducting cavities alone with all superconducting cavities detuned. Then one superconducting cavity was tuned. Keeping the generator power constant, klystron phase was shifted so that the second term of Eq.(2) became zero. This procedure was done on all cavities one after another. All mentioned above was done using electron beam and positron beam, respectively. Difference of wave guide length and cavity allignment errors were derived from the phase shift of each cavity mentioned above. Thus the phase of all superconducting cavities were adjusted each other within 2 degrees. Finally the phase between the superconducting cavities and normal conducting cavities were adjusted maximizing the synchrotron frequency of the beam.

5. Higher Order Modes

The KEK 5-cell cavity uses two coaxial HOM couplers mounted at right angles to each other at the beam pipe opposite to the input coupler. The external Q for the fundamental mode of any HOM coupler is greater than 10^{10}. The DESY 4-cell cavity uses a set of three coaxial two-stub HOM couplers; one is mainly for TM_{011} and two are for TE_{111}, TM_{110} and TM_{012}.

Typical damping of most prominent HOM's are listed in Table 6. Due to the high designed current for HERA condition, strong damping is necessary for the DESY couplers. For longitudinal modes QL=600 and for transverse modes QL is smaller than 20000. Also in CERN and KEK, the most prominent HOM's are sufficiently damped.

In the KEK operation in T-MR, measured output power is typically 50 W per one coupler for TM011 at 8 mA. No beam instability caused by HOM's in the superconducting cavities has been observed in T-MR.

Table 6 Typical damping of most prominent HOM's

	CERN		KEK		DESY	
	R/Q	QL	R/Q	QL	R/Q	QL
TM011			22	30-60	5.4	4.8
(longi.)	46	8	56	10-20	48	0.6
	108	13	103	10-30	111	0.6
TE111	8.3	27	25	30-80	17.0	6.2
(trans.)	7.2	19	33	15-35	14.6	4.8
TM110	11	58	13	28-82	4.3	5.1
(trans.)	7.4	94	26	68-134	22.4	7.0
			7.2	131-300	15.4	15.0

(R/Q is in ohm and QL is in 10^3.)

For the dipole modes R/Q is defined 50 mm out of beam axis.

6. Concluding remarks

Superconducting cavities have been operated successfully in accelerators. It has been confirmed that the superconducting cavities can be used stably for experimetal use. For more than 5000 hours the cavities have indicated no essential degradation of the cavity performance. The study of long-term performance should be continued in longer range of period.

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