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# PERFORMANCE OF SRF SYSTEMS IN STORAGE RINGS

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Large-scale application of superconducting RF(SRF) systems to storage rings, electron linacs and ion accelerators have been completed or are under construction at many laboratories. The existing SRF systems have been operated for physics experiments for several years. For storage rings, there are three existing large-scale SRF systems. At KEK, the superconducting RF system in TRISTAN-MR(T-MR) was completed in 1989 and has been operating for electron-positron colliding beam experiments for more than three years. In LEP at CERN and in HERA at DESY, constructions of SRF systems are in progress and recently beam acceleration was performed.

This paper describes long-term performance and operational experiences of the SRF systems which have been operated in storage rings. The SRF systems have been successfully operated with gradient of 4–5 MV/m and beam current of more than 10 mA. Most of the cavities show no degradation of performances for several years. Some troubles and cures during the long-term operation in T-MR are also reported.

## 1 INTRODUCTION

Research of superconducting (s.c.) cavities aiming at application to particle accelerators started at Stanford University in the 1960's.[1] Since then, remarkable advancement has been made in several laboratories. In order to apply the s.c. cavities to storage rings, several beam tests have been performed in storage rings, in CESR at Cornell University,[2] in PETRA at DESY,[3] in TRISTAN-AR at KEK[4] and in SPS at CERN.[5] These beam tests have brought us technology and experiences necessary to realize a large-scale application of s.c. cavities to storage rings. Successful results in the beam tests together with great advancements in basic research such as materials, surface treatments, manufacturing, etc., have shown great applicabiltiy of s.c. cavities to storage rings.

Now large-scale applications of SRF systems to storage rings have been completed or are under construction at KEK, CERN and DESY. There are some applications of s.c. cavities also to electron recyclotrons or ion accelerators. Table 1 shows present status of large-scale SRF systems in storage rings or electron recyclotrons.[6] In addition, constructions of electron linacs using s.c. cavities are going on at Frascati, JAERI and Saclay. There are some common features between SRF systems in storage rings and in recyclotrons. The main differences in view of operation of the SRF system come from the high beam current to be dealt with and the accuracy of cavity field control needed for beam quality. The typical beam current in storage rings is more than 10 mA, that is much more than that in recyclotrons which is typically 100 $\mu$A. On the other hand, more precise control of cavity field may be needed in recyclotrons. This report is mainly concerned with performances of SRF systems in storage rings.

## 2 OVERVIEW OF THE OPERATION STATUS

The first large-scale SRF system was constructed at KEK. Sixteen 5-cell s.c. cavities started to operate in TRISTAN-MR in 1988.[7] The system was completed by adding other 16 cavities in 1989.[8,9] They have been operating to provide the necessary accelerating voltage for electron-positron colliding beam experiments.

Table 2 shows the operation summary of the SRF system for the physics experiments. In the first phase of the operation aiming at high energy until Dec. 1989, the cavities had been operated with the average gradient of 4.4–4.7 MV/m for one and a half years. The beam energy was raised up to 32.0 GeV using 29 superconducting 5-cell cavities with the total accelerating voltage of 200 MV and 104 normal conducting 9-cell cavities with 320 MV. In the second phase of the operation aiming at high luminosity since Feb. 1990, the beam energy has been fixed at 29.0 GeV and the average gradient was lowered to 3.5 MV/m because greater importance was attached to stable operation for large beam current rather than higher gradient. They have been operating stably with beams of 13mA. Since the first cooldown of the first 16 cavities they have undergone cooldown and warm up six or seven times. Total operation time of these cavities at 4.4 K amounts to 14,000 hours and they have been operated for the electron-positron colliding beam experiments for more than 7,500 hours.

At CERN one or two 4-cell cavities have been operated in SPS since 1988 in the lepton cycles. Two Nb/Cu cavities have provided 17 MV with a gradient of 5.5 and 4.5 MV/m, respectively. They plan to install two additional Nb/Cu cavities in 1992, and these s.c. cavities will be able to supply the necessary RF voltage for the SPS as LEP injector.[10] Large-scale application of 192 cavities in LEP to upgrade the energy is now under construction. Three modules, each consists of four 4-cell cavities, have been installed in LEP and started to operate providing 75 MV to accelerate beam of 3.8 mA.[11]

At DESY sixteen 4-cell cavities will be used in HERA electron ring to accelerate beam of 60 mA. Twelve cavities have been installed and operated with 37 MV to accelerate beam of 4.5 mA.[12]

Construction of S-DALINAC has been completed at Darmstadt. The injector composed of a 5-cell and two 20-cell cavities has been operated for physics experiments since 1987. The main linac composed of eight 20-cell cavities was completed recently. They have been able to recirculate the beam twice for three passes through the main linac since Dec. 1990. In pulsed operation with 50% duty factor, the beam energy of 104 MV was achieved.[13] At CEBAF, a large-scale application of 338 cavities for 5-pass recirculating linac of 4 GeV is now under construction.[14]

TABLE 1: Large-scale application of superconducting cavities for electron accelerators

∗ design value

| Laboratory | KEK | CERN | DESY | HEPL | Darmstadt | CEBAF |
|---|---|---|---|---|---|---|
| Accelerator | TRISTAN | LEP | HERA | Recyclotron | Recyclotron | Recyclotron |
| Energy | 32GeV | 64GeV | 33.5GeV | 130MeV | 130MeV | 4GeV |
| Purpose | $e^+e^-$ collider | $e^+e^-$ collider | $e^-p$ collider | FEL<br>Nucl.Phys. | FEL<br>Nucl.Phys. | Nucl.Phys. |
| Accelerating Structure | | | | | | |
| Material | Nb | Nb-Nb/Cu | Nb | Nb | Nb | Nb |
| Frequency | 508MHz | 350MHz | 500MHz | 1.3GHz | 3GHz | 1.5GHz |
| Operating Temperature | 4.2K | 4.2K | 4.2K | 1.9K | 2K | 2K |
| Number of Cells | 5 | 4 | 4 | 1-3-6m | 5–20 | 5 |
| Number of Structures | 32 | 192 | 16 | 1-1-5 | 1–10 | 338 |
| Maximum Gradient | 9.4MV/m | 10MV/m | 8.5MV/m | - | 7.2MV/m | 15.3MV/m |
| Operating Gradient | 3–6MV/m | $5^*$ (Nb)<br>6∗ (NbCu) | $5^*$MV/m | 2–3MV/m | 3– 7.2MV/m | $5^*$MV/m |
| Commissioning | 16 (1988)<br>16 (1989) | 4 (1990)<br>28 (1991) | 12 (1991) | 1974 | 1989 | 1994 |
| Upgrade | - | +160(1994) | +4 | - | - | - |

*Updated from* Table III of Reference 6

TABLE 2: Summary of the operation of SC Cavities in TRISTAN-MR at KEK

| Period | | Number of cav. | | Total Vc | Eacc(ave.) | Energy | Current | Physics Run |
|---|---|---|---|---|---|---|---|---|
| | | (at 4K) | (operated) | (MV) | (MV/m) | (GeV) | (mA) | (days) |
| [High-energy run] | | | | | | | | |
| 1988 | Nov – Dec | 16 | 16 | 105 – 109 | 4.4 – 4.6 | 30.0 | 10 | 18 |
| 1989 | Jan – Mar | 16 | 14 | 82 – 88 | 4.0 – 4.2 | 30.4 | 9 | 49 |
| | May – Jun | 14 | 14 | 87 | 4.2 | 30.4 | 10 | 17 |
| | Jun – Jul | 16 | 16 | 105 | 4.4 | 30.7 | 10 | 37 |
| | Oct – Dec | 30 | 28 – 29 | 190 – 200 | 4.6 – 4.7 | 32.0 | 12 | 25 |
| [High-luminosity run] | | | | | | | | |
| 1990 | Feb – Mar | 32 | 31 | 160 | 3.5 | 29.0 | 12 | 37 |
| | Apr – May | 32 | 30 – 31 | 160 | 3.5 – 3.6 | 29.0 | 12 | 25 |
| | May – June | 32 | 28 – 30 | 150 – 160 | 3.6 | 29.0 | 13 | 39 |
| | Jul | 30 | 25 | 130 | 3.5 | 29.0 | 13 | 31 |
| 1991 | Jan – Jul | 32 | 29 – 30 | 140 – 145 | 3.3 | 29.0 | 9 | 36 |
| Total accumulated time of cavities | | | | | | | | |
| | | | at 4.4 K : | | | 14,000 hours | | |
| | | | operated for physics experiments : | | | 7,500 hours | | |
| | | | (machine tuning time is not included) | | | | | |

## 3 ENVIRONMENTAL CONDITIONS

### *3.1 Vacuum pressure in the ring*

Even if each cavity has a powerful vacuum pump, the cavity itself acts as a powerful cryo pump, so that a large amount of gas adsorption at the cavity surface is expected in a long term of operation. Fig. 1 shows a change of vacuum pressure in each cavity in T- MR at KEK as a function of location during six months of continuous operation.[15] The cavities are located in a straight section between two arcs. The interaction region divides it into two cavity sections. All data were taken when beams of 11 – 13 mA were kept at 29 GeV. At the beginning of the run (Mar. 1990), the vacuum pressure in the cavity near the interaction region or near the arc sections was about $1 \times 10^{-9}$ Torr, while in other cavities less than $5 \times 10^{-10}$ Torr. After two months of operation (Apr. 22) it became worse to $3 \times 10^{-9}$ Torr in the cavities near the arc sections and near the interaction region. After four months of operation (Jun. 16) it became worse to $3 \times 10^{-9}$ Torr in almost all cavities. This indicates that the gas from the arc sections and from the interaction region was adsorbed in the nearest cavities at the beginning and then the vacuum pressure rise extended gradually into further cavities.

This fact was also confirmed by desorbed gas measurements in each cavity during warm up after 60 days of another operation period (Oct. – Dec. 1989).[16] The amount of desorbed gas during warm up was over 10 mTorr corresponding to 5 monolayers in cavities near the arc sections or near the interaction region, while about one mTorr corresponding to less than one monolayer in other cavities. In a short shut down in June 1990 an accident happened that the compressors of the refrigerator stopped. All the cavities were warmed up to between 7 and 20 K. Most of hydrogen gas that had been adsorbed at the cavity surface was desorbed and pumped out. The vacuum pressure in the cavities recovered to the original level as that at the beginning of the operation.

### *3.2 Radiation in the ring*

Radiation caused by the cavities at the operation field without beams was measured in T- MR using TLD. It differed from one cavity to another, from less than 10 R/hour to over 5 kR/hour.

Fig. 2 shows radiation caused by beams during operation for physics experiments measured using RAD color.[17] Every cryostat has a mask on a warm beam pipe at the bending side of it to prevent synchrotron radiation from the arc section. Radiation was measured at the bending side of each mask. Strong radiation of over 40 kR/mAhour was observed around the cavities near the arc sections. There is no evidence that the strong radiation has caused any degradation of the cavity performances. However, the strong radiation caused some troubles such as frequent trips in the cavity and hardware failures, which will be mentioned later.

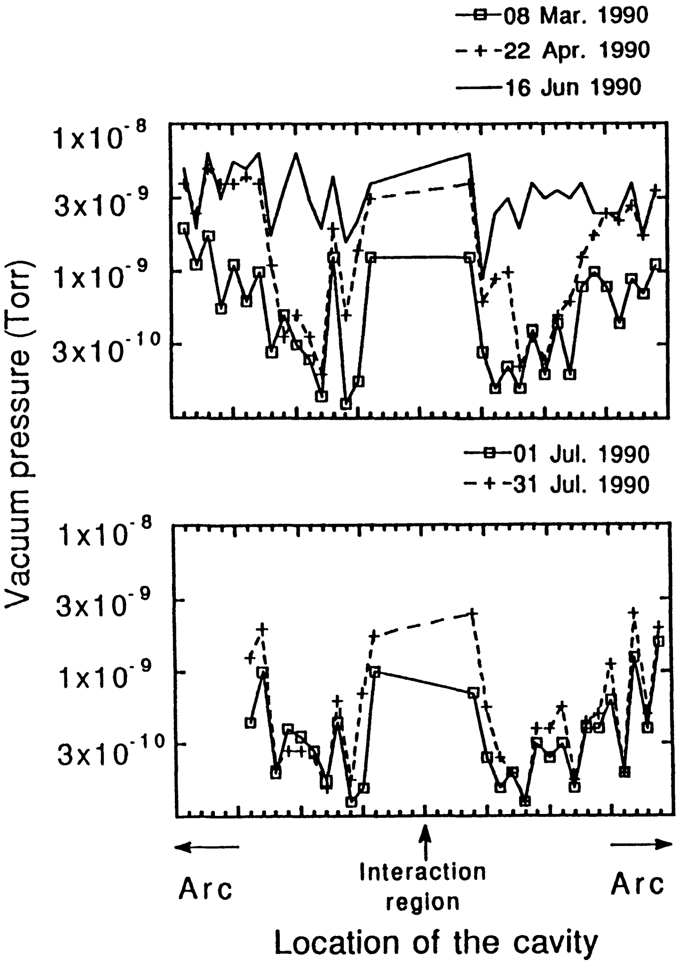

FIGURE 1: Change of vacuum pressure in each cavity as a function of the location during six months of operation in TRISTAN-MR: (a) before and (b) after the warm up to 7 – 20 K.

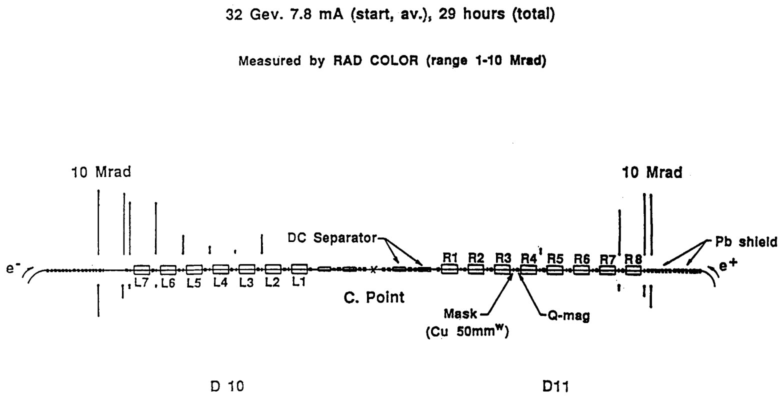

FIGURE 2: Distribution of radiation measured with beams in TRISTAN-MR.[17]

## 4 CAVITY PERFORMANCE

### *4.1 In bench tests*

Before installed in storage rings, each cavity had been tested in a vertical cryostat (vertical test) and in a horizontal cryostat (horizontal test). In the vertical test high power input couplers and HOM couplers were not installed. In the horizontal test, on the other hand, all the couplers were attached. At KEK it was observed that in some cavities there were degradation of the maximum accelerating gradient (Eacc, max) and the $Q$-value in the horizontal tests compared with the vertical tests. This degradation is considered to be due to dust contamination during the assembly in the cryostat. Nevertheless, all cavities except one exceeded the design value of 5 MV/m. All of 12 cavities installed so far in LEP at CERN exceeded the design value of 5 MV/m in bench tests. At DESY, all cavities except one exceeded the design value of 5 MV/m in the horizontal tests.

### *4.2 In storage rings*

Cavity performance such as the maximum accelerating gradient (Eacc, max), the $Q$ value and the electron loading has been measured at every shut down of the machine of T- MR at KEK. Fig 3 shows the distribution of Eacc, max measured just after the first cooldown of the first 16 cavities (Nov. 1988), just after the first cooldown of the last 16 cavities (Oct. 1989) and after two or three years of operation (Jul. 1991).

Fig. 4 and Table 3 show the change of Eacc, max and the $Q$-value of all cavities as a function of days. The results are summarized as follows:[15]

(a) Most of the cavities, 25 cavities among 32, show no clear degradation during the long-term operation and under several times of cool down and warm up. The average Eacc, max of them has been kept between 6.7 to 7.0 MV/m.

(b) The Eacc, max of four cavities (10C#3, 10C#4, 10D#2 and 10D#3) once decreased, but after warm up to room temperature or even to 20 K they recovered to the previous

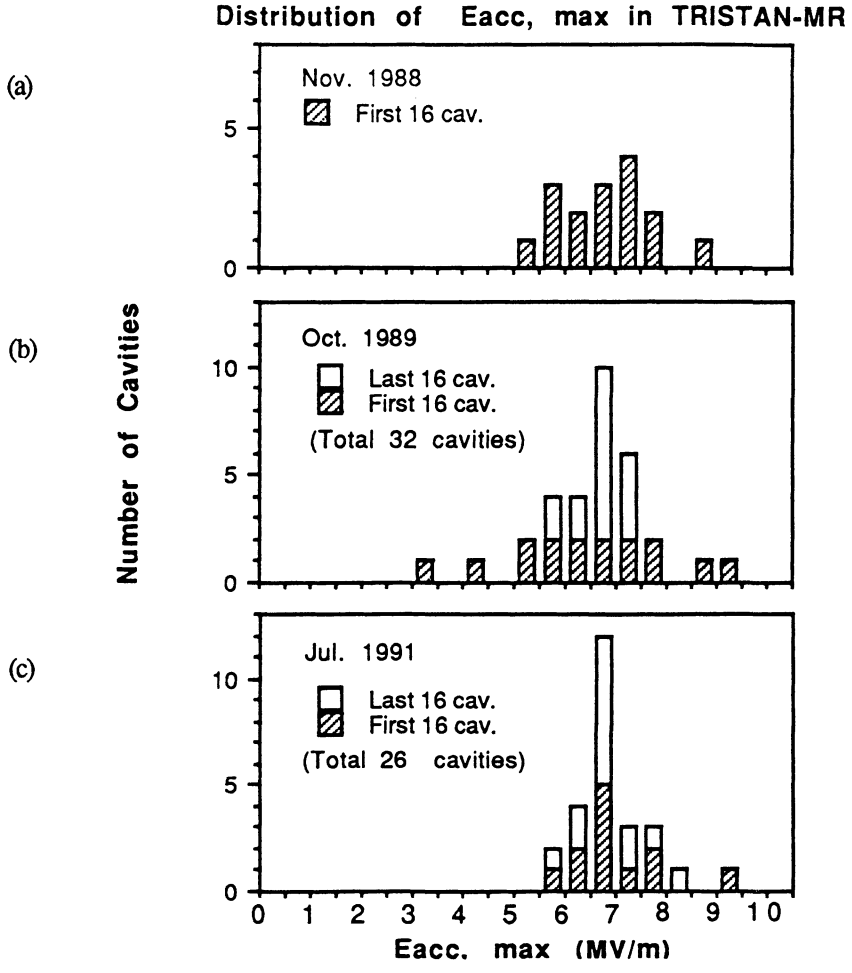

FIGURE 3: History of distribution of Eacc, max of all cavities in TRISTAN-MR: (a) just after the first cool down of the first 16 cavities (Nov. 1988), (b) just after the installation of the last 16 cavities (Oct. 1989) and (c) after two or three years of operation.

values. The temporary degradation of these cavities was found to be closely related with frequent interlock actions.
(c) Three cavities (10B#1, 10B#2 and 11C#3) degraded and have not recovered. Two of them (10B#1, 10B#2), which are located in the same cryostat, began to degrade suddenly only after one week of operation. It is thought to be caused accidentally by dust from somewhere. They are still used in the operation with lower gradient of 2.5 or 3.0 MV/m. One cavity (11C#3), whose Eacc, max degraded to 3 MV/m, is the lowest value among all cavities, this is also the cavity that had leaked at the input coupler and could not recover after the re-treatment. It should be discussed separately from the long-term performance. This one has been detuned and out of operation. The performances of these three cavities show no clear dependence on the cool down and warm up cycles. They also have low $Q$-values at relatively lower field (Table 3) and heavy electron loading.

Table 4 shows Eacc, max of all cavities installed in S-DALINAC measured with electron beam. The average Eacc, max of cavities with high RRR of 280 is higher than that with lower RRR of 30. Present limitation are not the cavity fields but the capability of the refrigerator.[13]

## 5 COUPLER PERFORMANCE

### 5.1 *Input couplers*

Table 5 shows an operation summary of input couplers at KEK.[18] Before cool down of the cavities, input couplers were processed at a test stand and in the cryostat at room temperature. They were tested up to 200 kW of transmission power and 75 kW under total reflection condition. After TiN coating was adopted, aging time was reduced to 2 – 5 hours, compared with 4 – 13 hours without the coating.[19] Four couplers leaked at the ceramic windows during the processing without the arc detection system. After the arc detection was installed, no coupler leaked during the processing.

In usual operation in the ring, the input power to one coupler is 60 kW of transmission power with beams of 10 mA and less than 30 kW under total reflection condition without beams. During three years of operation, six couplers leaked at the ceramic windows. For three cases, cavities were able to operate after replacement of the input couplers. Other three cavities were damaged so heavily that they needed retreatment of the surface. Another trouble in the couplers occurred at the polyethylene disks, located on the atmospheric side of the ceramic window. Two polyethylene disks were burnt seriously, one of which led to a leakage of the ceramic window. Logged data indicate that the burning advanced gradually for two months. All polyethylene disks were replaced by Teflon disks.

### 5.2 *HOM couplers*

Loaded $Q$ for prominent HOMs of each cavity in T-MR had been measured in horizontal tests. Loaded $Q$ for the most dangerous longitudinal modes having large $R/Q$ values (TM011-0, $1\pi/5, 2\pi/5$) are sufficiently lowered to $1 - 4 \times 10^4$ and the total impedance for them is less than $2\text{M}\Omega$ in most cases.[19]

TABLE 3: $Q$ value measured in the horizontal tests and in T-MR at KEK

| Cavity No. | $Q$-value ($\times 10^9$) at Eacc (MV/m) | | | | |
|---|---|---|---|---|---|
| | Horizontal test | T-MR Jul.'89 | T-MR Oct.'89 | T-MR Jul.'90 | T- MR Jul.'91 |
| 10A#1 | 1.6 (6.6) | 2.2 (5.5) | 2.3 (6.0) | 2.0 (6.0) | 2.0 (6.0) |
| 10A#2 | 2.1 (6.5) | 2.2 (6.0) | 2.0 (6.0) | 1.7 (6.0) | 1.5 (6.0) |
| 10A#3 | 2.6 (5.1) | 1.3 (5.0) | 1.8 (5.0) | 1.4 (5.0) | 1.5 (5.0) |
| 10A#4 | 1.9 (6.3) | 1.9 (6.0) | 2.5 (6.5) | 1.5 (6.5) | 1.7 (6.0) |
| 10B#1 | 1.7 (7.0) | 0.58(4.0) | 0.40(4.0) | 0.28(4.0) | 0.54(3.5) |
| 10B#2 | 1.6 (6.0) | 1.1 (4.4) | 1.1 (4.5) | 1.3 (4.5) | 0.79(4.5) |
| 10B#3 | 2.8 (6.8) | 2.2 (6.0) | 1.8 (5.0) | 1.9 (6.0) | 2.0 (6.0) |
| 10B#4 | 2.4 (7.0) | 2.5 (6.0) | 2.6 (6.0) | 2.4 (6.0) | 2.3 (6.0) |
| 10C#1 | 2.1 (7.0) | | 2.2 (6.0) | 1.9 (6.0) | 2.0 (6.0) |
| 10C#2 | 1.5 (7.0) | | 2.4 (6.0) | 1.9 (6.0) | 1.7 (6.0) |
| 10C#3 | 2.5 (6.0) | | 2.8 (6.0) | 2.8 (4.0) | - |
| 10C#4 | 1.6 (6.0) | | 2.3 (6.0) | 3.0 (3.5) | 1.9 (4.8) |
| 10D#1 | 1.5 (6.0) | | 2.2 (6.3) | 2.1 (6.0)* | 1.9 (6.0) |
| 10D#2 | 2.0 (5.0) | | 1.6 (6.3) | 2.0 (6.0)* | 1.9 (6.0) |
| 10D#3 | 2.5 (6.0) | | - | 1.8 (6.0)* | 1.7 (6.0) |
| 10D#4 | 1.6 (6.0) | | - | 1.9 (6.0)* | 1.8 (6.0) |
| 11A#1 | 2.3 (6.9) | 2.2 (6.0) | 2.2 (6.3) | 2.2 (6.0) | 2.4 (6.0) |
| 11A#2 | 1.5 (4.2) | 1.5 (5.0) | 1.1 (5.8) | 1.2 (5.5) | 1.5 (5.5) |
| 11A#3 | 2.4 (5.4) | 2.1 (5.0) | 2.4 (5.2) | 2.2 (5.0) | 2.2 (5.0) |
| 11A#4 | 1.4 (5.9) | 2.1 (6.0) | 3.1 (6.3) | 2.0 (6.0) | 1.7 (6.0) |
| 11B#1 | 2.1 (8.0) | 2.2 (6.0) | 2.1 (6.0) | 2.3 (6.0) | 2.0 (6.0) |
| 11B#2 | 1.9 (5.5) | 1.4 (5.5) | 1.1 (5.5) | 2.2 (5.5) | 1.8 (5.5) |
| 11B#3 | 1.9 (6.0) | 1.3 (6.0) | 1.6 (6.0) | 2.0 (6.0) | 1.4 (6.0) |
| 11B#4 | 2.0 (6.0) | 1.5 (6.0) | 1.6 (6.0) | 1.5 (6.0) | 1.6 (6.0) |
| 11C#1 | 2.1 (6.0) | | 1.8 (6.2) | 1.7 (6.0) | 1.5 (6.0) |
| 11C#2 | 1.5 (5.0) | | 1.4 (5.1) | 2.6 (5.0) | 1.4 (5.0) |
| 11C#3 | 1.2 (2.5) | | 0.92(2.6) | - | - |
| 11C#4 | 2.0 (6.0) | | 2.0 (6.2) | 2.3 (6.0) | 3.0 (6.0) |
| 11D#1 | 2.3 (6.0) | | 2.0 (5.5) | 2.1 (5.5) | 2.1 (5.5) |
| 11D#2 | 2.2 (6.0) | | 2.1 (6.0) | 2.1 (6.0) | 2.4 (5.5) |
| 11D#3 | 2.6 (6.0) | | 1.9 (5.5) | 2.0 (5.5) | - |
| 11D#4 | 2.4 (4.5) | | 1.5 (5.5) | 1.8 (5.0) | - |

*Jan. '91

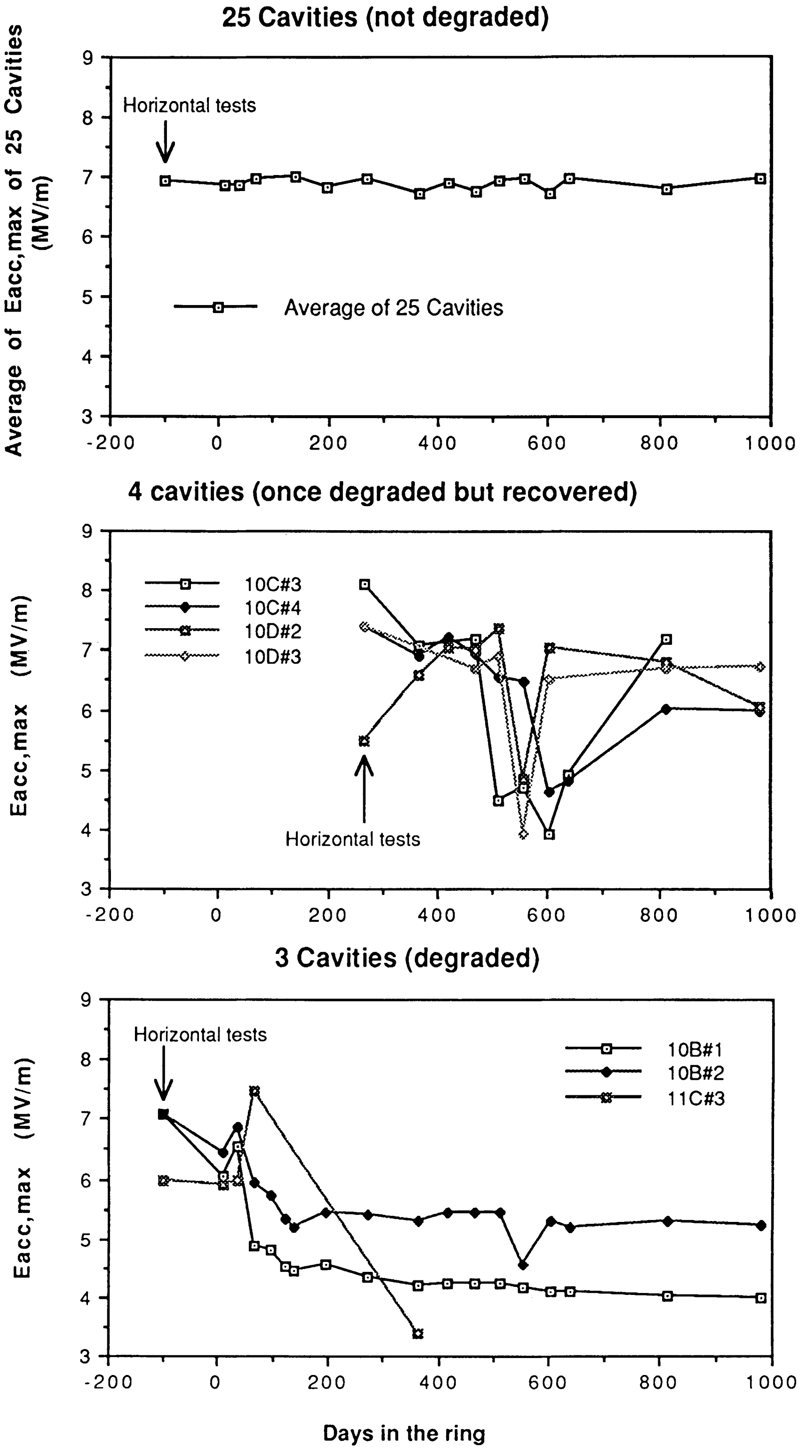

FIGURE 4: Change of Eacc, max of all cavities as a function of days after installations in TRISTAN-MR. (a) Average of Eacc, max of 25 not-degraded cavities, (b) Eacc, max of 3 cavities which once degraded but recovered and (c) 3 degraded cavities.

TABLE 4: Accelerating field of cavities installed in S-DALINAC

| # of cells | RRR | Eacc (MV/m) |
|---|---|---|
| 5 | 30 | 7.0 |
| 20 | 30 | 3.0 |
| 20 | 100 | 6.3 |
| 20 | 280 | 6.5 |
| 20 | 280 | 7.2 |
| 20 | 280 | 4.4 |
| 20 | 30 | 3.6 |
| 20 | 280 | 4.6 |
| 20 | 100 | 5.4 |
| 20 | 280 | 6.4 |
| 20 | 280 | >3.4 |

TABLE 5: Summary of the high power performance of the input couplers for T-MR at KEK

| | Numbers of Tested Couplers | TiN Coating | Arc Detection | Numbers of Leaked Windows |
|---|---|---|---|---|
| Processing | 24 | No | No | 4 |
| at Test Stand | 10 | No | Yes | 0 |
| | 24 | Yes | Yes | 0 |
| Processing | 28 | No | No | 0 |
| in Cryostat | 10 | Yes | No | 1 |
| at room temp. | 18 | Yes | Yes | 0 |
| Operation | 38 | Yes/No | No | 4 |
| at 4.4 K | 18 | Yes | Yes | 2* |

* One leak was caused by the failure of polyethylene disk.

HOM extracted power in the ring was measured either by summing up power of each mode observed with spectrum analyzer, or by direct measurement using a calorimetric power meter. The measurements were compared with calculations. The loss parameter below the cut-off frequency of the beam pipe for the KEK cavity is 0.41 V/pC, which gives power lost by beams of 4 bunches × 2 mA to be 66 W per one cavity, assuming no resonant build up. Measured power in the ring was 70 – 100 W per cavity at the same current. In the LEP cavity at CERN, loss parameter below the cut-off is 0.22 V/pC, which gives power loss of 10.9 W for a beam of 0.75 mA, also assuming no resonant build up. Measured power was 12 W.[20] Neither strong resonant build up nor clear instability caused by HOMs has been observed up to 13 mA in T-MR at KEK.

## 6 CONTROL AND OPERATIONAL EXPERIENCE IN TRISTAN-MR

### *6.1 RF control*[21]

There are some similarities between RF control system for s.c. cavities and that for n.c. cavities. Some parts of the control system can be used commonly. Most differences come from (1) high beam-induced voltage in s.c. cavities due to higher loaded $Q$ than in n.c. cavities and (2) interlock system related with quenches.

The beam-induced voltage in the KEK cavity is 5 MV/m at beams of 12 mA with the loaded $Q$ of $10^6$ and $R/Q$ of 400 $\Omega$/m, this is comparable to the operation gradient. At the injection energy, this is more severe because of the lower operation gradient. The high beam-induced voltage should be taken into account in designing the cavity tuning system and recovery procedure, that is switching on tripped cavities keeping the beam stored. In the usual method of tuning in storage rings, the cavity tuning is controlled so that the reactive component of impedance caused by beams can be compensated, so that the RF generator sees the load as real impedance. The Robinson stability limit was calculated in the case of T-MR, that showed about 20 degrees of detuning offset is necessary at the injection energy. Consequently the detuning offset is operated in a programmed pattern, shifted by 30 degrees at the injection and restored to 5 degrees at the maximum energy.

Some cavities are switched off sometimes by interlocks. The tripped cavities should be switched on again without disturbing the stored beam. The procedure to switch on the RF was designed carefully to cope with the high beam-induced voltage.

Besides ordinary interlock system used for n.c. RF system, SRF system needs much more rigorous interlocks to protect the cavity. Quenches are detected by the decay of the cavity field or a helium pressure rise. The fast quench detector measuring the field decay is found to be useful not only to detect a thermal quench with a typical time constant of field decay of several tens of msec, but also to detect fast decay related with a discharge in the cavity, which will be mentioned later.

Calibration of the amplitude of the cavity field was done based on two independent methods: one is based on external $Q$ of the monitor port, measured from external $Q$ of the input coupler and transmission power. The other is from measurement of synchrotron frequency of the beam. Both have agreed within 5%.

The phase of the cavity field was adjusted taking advantage of the high beam-induced voltage. With a constant input power to the cavity, amplitude of the cavity field depends on the relative phase between stored beam and input *rf* power. The relative phase of each cavity was adjusted measuring the beam-induced voltage with stored beams. This method enabled us to adjust it with high accuracy.

### *6.2 Some troubles and cures during the long-term operation*

*6.2.1 Hardware troubles* Filters installed in HOM couplers to reject the fundamental frequency had been adjusted for each coupler before assembling the cryostat. External $Q$ for the fundamental mode was sufficiently high: even in the worst case was $2 \times 10^{10}$. However, sometimes extraordinary fundamental power came out of the HOM couplers, increasing to 1 kW with a time constant of 10 minutes. This 'thermal run away' is explained as follows: a quench caused by multipactings occurs in the HOM couplers. The inner cylinder of the filter, which is not cooled by liquid helium but cooled only by thermal conductivity, is heated and expanded. That changes the filter frequency by 2 MHz when it is heated up to 300 K. The frequency change together with large dissipation due to the breakdown lowers the external $Q$ for the fundamental mode. The 'thermal run away' was also observed in SPS at CERN. In order to cure this, an interlock system was installed at KEK, which switch the RF off when abnormal fundamental power is detected through any HOM couplers. In case of CERN, this is manageable in the pulsed operation in SPS.

Some N-type connectors and cables in vacuum vessels to extract HOM power were burnt in the early stage of the operation. Some of them were caused by extraordinary fundamental power triggered by quenches in the HOM couplers, which was cured by interlocks, as mentioned above. Others were caused by HOM power with beam current of 14 mA. During the operation in 1990 the beam current had been restricted to less than 13.5 mA to avoid this trouble. In the summer of 1990 the HOM extraction system was improved using larger ceramic connectors. This system is expected to be safe with over 20 mA of beam current.[18]

Some of piezoelectric transducers, which are located outside the cryostat to tune the cavity, failed. As for five of them, plastic bolts to stack the piezoelectric elements were broken probably due to radiation damage. All the piezoelectric tuners were replaced with new type ones using stainless bolts with springs instead of the plastic bolts. However, almost half of them failed within six months of operation. The reason of these failures is not known clearly. It may be suggested that they are not tough enough against a fast change of applied voltage.

Leak of cavity vacuum occurred in two cryostats. Location of the leak could not be identified because the leak stopped after warming up. After re-assembling the cryostats, they were able to operate again. It is thought that they leaked at the Indium sealing.

Troubles related with the input couplers were already mentioned in section 5.

*6.2.2 Trips in the cavity*[15] When some interlock action works, the RF switch for the klystron which drives the tripped cavity is shut off. Frequent interlock actions are undesirable because they sometimes cause shorter lifetime of the stored beam, more background noise at detectors of physics experiments or beam loss in the worst case.

Fig. 5 shows typical examples of a characteristic feature observed when the trip occurred. The pick up signal falls down to almost zero within a very short time of less than 10 $\mu$s, that is much shorter than the filling time of the cavity taking account of the beam loading (600 $\mu$s without beam and 300 $\mu$s with 10 mA). The fast decay is also observed in the signal of the fundamental mode from HOM couplers. This indicates that the stored energy in the cavity decays with the same time constant. The reflection power from the cavity also changes at the same time. A sharp spike signal is sometimes observed in the fundamental mode from the HOM couplers.

It was found that some of the trips are caused by a discharge in the cavity due to multipactings in HOM couplers triggered by synchrotron radiation from the beam. It was able to reduce the occurrence of the trip by precise alignment of the masks and by RF processing of the HOM couplers. It was also found that some of the other trips had relevance to some bad conditions of the input couplers.

*6.2.3 Further precise adjustment required for the high luminosity run*[22] In T-MR , a lot of laborious efforts were needed in the beam tuning process after the superconducting quadrupole magnets were installed in the interaction regions to make mini-beta optics for the high-luminosity run. Some of the difficulties were related with excessive sensitivity of beams to change of closed orbit distortions (COD's). It was found that some of the change of COD were caused by interaction between beams and the accelerating system. They required much more precise adjustment of the RF system as follows:

(1) difference of COD's between electron and positron beams: The energy loss by the synchrotron radiation is compensated at localized RF stations. This makes energy difference between both beams, that causes different COD's between both beams due to non-zero dispersion at arcs. In order to cure this, the RF phase of each station was re-adjusted so that it minimized the difference of COD's.

(2) difference of COD's between low and high current beams: Because HOM losses are higher in n.c. cavities than in s.c. cavities, the effective accelerating voltage decreases much more in n.c. cavities than in s.c. at high beam current. Then the ratio of effective accelerating voltage of n.c. to s.c. cavities changes with beam current. At the injection energy the change of COD caused by the change of the beam current limited the stored current. It was solved making the ratio of accelerating voltage proportional to the ratio of HOM impedance during the beam injection to minimize the difference of COD's.

## 7 CONCLUSION

The SRF systems have been operated successfully in the storage rings for several years for physics experiments. Most cavities have shown no degradation during the long-term operation. Strong radiation has not caused degradation of cavity performance essentially. However, effective shielding for the radiation is desired to reduce failure of attachments and trips in the cavity. Operational experiences with them have provided us with valuable

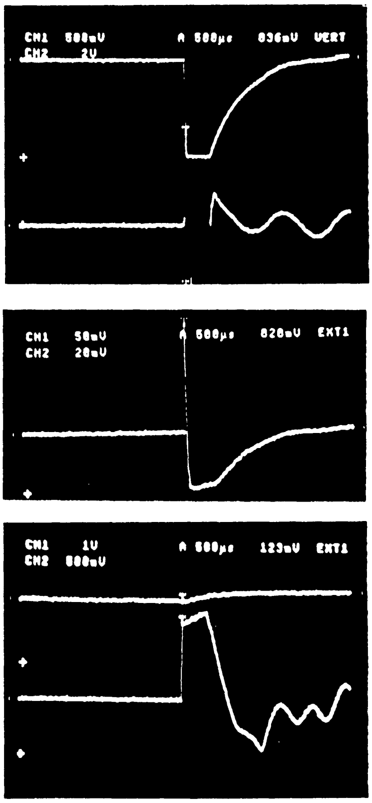

FIGURE 5: Characteristic features of the trip in the cavity observed in TRISTAN-MR (5 msec/full span)

information about performances of SRF systems in storage rings, which would also be of great help to future applications.

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