WHAT DID WE LEARN FROM STORAGE RING TESTS?

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I. Summary of Beam Tests Completed and Planned

In chronological order, beam tests which have been conducted in storage rings have included Cornell's test in 1982 of two 5-cell, 1500 MHz muffin-tin cavities in the CESR 8 GeV/beam e^+e^- storage ring[1,2]; a test by the Karlsruhe-CERN-DESY collaboration of the 1-cell, 500 MHz "DORIS" cavity in the PETRA 21 GeV/beam e^+e^- storage ring[3,4,5]; a test by CERN of a 5-cell, 500 MHz cavity in PETRA[6]; and a test by KEK of a 3-cell, 500 MHz cavity in the TRISTAN 8 GeV/beam e^+e^- accumulator ring[7]. Future tests include a continuation of the KEK test[7]; a test by DESY of two 9-cell, 1000 MHz cavities in PETRA[8,9]; a test by Cornell of two 5-cell, 1500 MHz elliptical cavities in CESR; and construction by CERN of 3 or 4 cell, 350 MHz spherical cavities.[10]

The Cornell 1500 MHz muffin-tins employed on-axis fundamental power waveguide coupling with enhanced coupling to unwanted fundamental passband modes; two higher order mode (HOM) waveguides were coupled through the walls of cells 1 and 5. The Karlsruhe-CERN-DESY cavity, tested in 1982, employed a coaxial loop fundamental power coupler; two coaxial HOM couplers with field transformers and intrinsic notch filters were mounted on the end wall of the cavity. The CERN 500 MHz cavity, tested in 1983, employed a coaxial loop fundamental power coupler; the HOM couplers, of which there was one on each cell, consisted of two types: electric probes required no notch filter because they were located on the equator, and loop probes were equipped with integral notch filters. The KEK 500 MHz cavity, tested in 1984, uses a coaxial loop fundamental power coupler; there is provision for up to two electric or magnetic HOM probes on each cell. The DESY cavities, to be tested in 1984, use on-axis waveguide fundamental power coupling; HOM coupling is achieved using one on-axis HOM waveguide coupler. The waveguides are ridged to reduce their dimensions and suppress the onset of overmoding. The Cornell elliptical cavities, to be tested in 1984, use on-axis fundamental power waveguide coupling, with enhanced coupling to unwanted fundamental passband members; HOM coupling is achieved using two on-axis waveguide couplers at right angles to each other. The CERN 350 MHz structure employs fundamental and HOM couplers which intersect the beam pipe at the end of the structure.

The CERN and KEK cavities are spherical, the DESY cavities are elliptical, and the Karlsruhe-CERN-DESY cavities are cylindrical.

II. Objectives and Results

Most beam test objectives fall into the categories of studies of instabilities, beam dynamics, HOM's, fundamental frequency, controllability, environmental factors, and reliability; the objectives will be discussed in this order.

A. Instabilities

1. Determine the ability to avoid instabilities caused by HOM's.

Instability thresholds depend on many factors including the electron energy, the number of cavities, the number of bunches, the bunch passage interval, the bunch length, the ZT^2/Q of the cavities (where Z is the impedance per unit length for infinite velocity particles, and T is the transit time factor), the Q_{ext} of the cavities, the spread in frequencies of the HOM's of the cavities, the central frequency of the HOM distribution (for a particular mode), the bunch charge, the vertical and horizontal beta functions at the cavity, the values of the tunes Q_x, Q_y, and Q_s, the Landau damping rate due to chromaticity, octupole moment, and RF curvature, the radiation damping rate, damping provided by feedback and other impedances, and the momentum compaction factor, to name a few.

Ideally, one would like to have all of these factors identical between the test and the intended application. However, it would be very expensive to have the total number of cavities without knowing if they were suitable or not, and, if one had the electron energy available in a ring, one wouldn't need any more cavities (unless the purpose was to replace Cu with Nb to save energy). Accordingly, it is necessary to use fewer cavities and lower energy in the test than one envisions in the final configuration, and to use computer calculations[11] of the instability probabilities in each case to make the comparison. It is also desirable to have the bunch spacing and bunch length in the test be as close as possible to the values intended in the final application; this is true because the importance of ZT^2/Q and of Q_{ext} for various modes changes dramatically as the bunch spacing and length change.

Define I_1 as the calculated instability threshold (for a particular type of instability) under the test conditions, I_2 as the calculated instability threshold under actual usage conditions, I_3 as the measured instability threshold or the highest current that can be reached (whichever is lower) under test conditions, and I_4 as the design current in the intended application. Define A implicitly as $I_3/I_1 = A \cdot I_4/I_2$. If A is greater than 1, the test indicates that the cavity design is acceptable. If I_3 is approximately equal to I_1, and if I_3 is also the instability threshold (rather than the current limit caused by some other factor), the test also provides a cross-check of the validity of the calculation.

The test ring, in addition to having a similar bunch passage interval and bunch length as in the intended application, should also have an impedance (including feedback) to which the test cavity or cavities make a significant perturbation. CESR is a desirable test ring in this respect, for there are normally only 14 normal conducting cells in the ring, and the higher modes in these cells are damped by a factor of 20 below their Q_0 values, and no feedback of any kind is needed when operating with a single bunch of current up to 50 mA.

Using the muffin-tin test in CESR as an example, I_1 = 0.25 mA at 0.1 probability and 1.0 mA at 0.4 probability for a longitudinal m = 1 instability; this was the lowest instability predicted. Instability was encountered at 2.6 mA, and was an m = 1 longitudinal instability. Since the calculation yields a probability distribution, the results cannot be compared directly, but are not inconsistent. Another way in which this measurement was made was that the frequency of the higher order modes were swept by tuning the cavity; the probability that the cavity was stable (averaged over frequency) at 2.5 to 4.5 mA was 0.28. The computer calculation predicted a value around 0.25. Since I_4 is less than I_2 for the design application, A is greater than unity, and the test indicates that the cavities are suitable for the purpose. In order to explore other beam instability modes, it is desirable to use selective feedback to suppress the ones whose thresholds have been crossed so that other thresholds can be searched for; this was done in the muffin-tin test to suppress the m = 1 and m = 2 longitudinal modes so that higher currents could be used to look for transverse instabilities.

No beam instabilities were seen in the DORIS or KEK cavity tests, and the only instability seen in the CERN cavity test was an m = 1 longitudinal instability caused by the 4/5 pi mode of the fundamental passband; this mode had an anomalously high ZT^2/Q in the beam test because of the way the pi mode field profile had to be tuned.

B. Beam Dynamics

1. Ability to Operate a Multi-Cell Cavity Without Problems Due to Other Passband Members (Field Flatness)

As discussed above, this problem was encountered in the CERN test due to the unusual way the pi mode had to be tuned; this is not a fundamental problem. An unexpectedly high Q_{ext} was found in one of the two muffin-tin modules for the 4/5 pi mode, causing an instability when this mode crossed an upper synchrotron sideband. This problem was caused by an improper adjustment of the cavity input coupling, and external irises and probe tuners used to compensate the problem for the pi mode caused this problem for the 4/5 pi mode. The problem is being handled on the Cornell elliptical cavities by performing mechanical adjustments on the coupler after fabrication, and by providing cold coupling adjusters. The DORIS cavity avoided this problem by having no other members of the fundamental passband except the mode used for acceleration.

2. Confirm Ability To Capture Injected Beam

All beam tests confirmed this ability. No surprises due to high Q_{ext} values of the fundamental, nor to different frequency of the fundamental (CESR) occurred.

3. Measure Bunch Length, Superconducting Cavity Only

The measured bunch lengths agreed with calculations.

4. Explore Bunch Lengthening and Shortening (Mixed Frequencies)

This was done in the CESR muffin tin test by varying the phases between the 1500 MHz SC cavity and the 500 MHz copper cavity. The bunch standard deviation was varied between 1.1 and 5.3 cm, as predicted.

5. Look For Anomalous Effects From High Q_s

This is a concern with high frequency cavities. Q_s values as high as 0.089 were used in the CESR muffin tin test without difficulties. These values were obtained by using both the 500 and 1500 MHz RF, appropriately phased for maximum Q_s.

6. Look For Field Curvature Effects

For speed-of-light particles, field curvature is a problem only for structures lacking cylindrical symmetry. Such effects are present in the muffin tin, and were compensated by rotating two consecutive cavities 90^0 about the beam axis relative to each other. To look for effects of the curvature, the RF fields in the two cavities were misphased 180^0 relative to each other; this procedure nulls the accelerating voltage and maximizes the curvature effects. With the superconducting cavities powered under this condition, the normal conducting RF was effectively prevented from capturing the beam.

7. Compare Coherent Tune Shifts vs. Beam Current, With and Without the Superconducting Cavity Installed

This quantity is a measure of the combined wideband and some narrowband resonance properties; it is a determining factor in the maximum single-bunch current that can be stored without encountering a mode-coupling instability. Installation of the superconducting cavity (with the fundamental tuned off resonance) produced less than a 20% change in both dQ_x/dI and dQ_y/dI in the CESR muffin tin test, indicating that the wideband impedance was not large compared to the expected value.

8. Compare Synchrobetatron Resonance Strength at High and Low Q_s

Higher Q_s values lower the synchrotron frequency multiple which is likely to become involved in a synchrobetatron resonance, assuming Q_x and Q_y values not near the integer; changes in the frequency also change the nonlinearity of the RF potential, and hence the coupling to various synchrobetatron resonances. This effect was studied in the CESR muffin tin beam test by using the 500 MHz RF alone, and by adding the 1500 MHz RF to it. The width of the synchrobetatron resonance was about 30% larger with the two RF's, but this was not considered a serious problem because the width was a small fraction of the synchrobetatron line spacing.

C. Higher Order Modes

1. Measure Heat Load Due to Higher Order Modes with Cavity Off Resonance and Unpowered

A systematic study of this question was performed during the CERN 5-cell beam test. 22 significant HOM's were tuned to revolution harmonics, and no increase in the cryogenic dissipation was observed in any of these cases. In the DORIS cavity test, the HOM Q_{ext} values were so low (300 - 10,000) that, in general, it didn't matter whether or not they were tuned to a revolution harmonic (since the power was extracted between bunch passages). It was established in this test that the HOM power dissipated in the LHe was less than 1 watt. A similar measurement was made in the CESR muffin tin test, where it was established that the HOM extraction efficiency was greater than 99.5%, and that the added cryogenic dissipation was less than 0.5 watts.

2. Look for a Reduction in Breakdown Field with Increased HOM Generation

Such a reduction would be expected if the breakdown field were caused by a defect being heated by the sum of the squares of the various mode fields, by a defect whose critical current was being exceeded, or by a field emission site whose emission would be enhanced whenever the local electric fields were momentarily in phase. No such effects were observed in the DORIS cavity test at currents up to 4 X 6 mA, nor in the CERN cavity test at currents up to 10 mA. The current in the CESR muffin tin test could not exceed 1 X 12 mA because of the previously mentioned difference in input coupling of the two modules; the fields in the two modules became intolerably different at currents above this value, but the breakdown field in the cavity with the higher field was not observed to drop noticeably with increasing beam current.

3. Look for Anomalously Narrow Resonances (Sweep Cavity Tune)

In the DORIS cavity test, no HOM Q_{ext} values exceeding $1 \cdot 10^4$ were reported. In the CERN cavity test, a member of the TM_{012} passband, which has very poor intercell coupling, was found to have a Q_{ext} greater than $5 \cdot 10^6$. In the CESR muffin tin test, the Q's of 76 HOM resonances were measured at frequencies above 1.995 GHz; the Q's ranged from 800 to 44,000, and none exceeded the value permitted for its frequency and ZT^2/Q, which was determined in the same measurement. By frequency sweeping, however, several very narrow (0 of the order of 10^8) "box modes" were identified. These modes, in principle, have no E_z component, but slight mechanical asymmetries cause this component to be present; the modes were found to cause a number of instabilities.

4. Compare HOM Power Generation with Theoretical Predictions

A careful measurement of this quantity was made in the DORIS cavity test for the four most important modes whose impedances had been previously determined. Power emerging from the two HOM couplers and the fundamental power coupler was measured, but it was not possible to measure power propagating down the beam tube. The measured power was 84% of the computed power. A similarly careful measurement of this quantity was made in the CERN cavity test, for the 22 HOM's tuned to resonance; within the measurement accuracy, the powers agreed with theoretical predictions. A measurement was made in the CESR muffin tin test to compare the total power emerging from the four HOM couplers with theoretical predictions at three different bunch lengths. The measured numbers of megawatts per square ampere ranged from 1.81 to 2.61. These numbers are 55 to 63% of the theoretical numbers; it is presumed that the missing power emerged from the fundamental power couplers (not measured) and through the beam pipes.

5. Compare Impedances and Q's of Individual Modes with Bench Measurements

This comparison was done for four modes in the DORIS cavity test, and for 22 modes in the CERN cavity test, as described in the preceding paragraph, with good agreement. The Q's and ZT^2/Q's were measured for 76 modes in the CESR muffin tin test, but they could be compared to bench measurements only on a statistical basis because of the high density of modes in the muffin tin structure and because of appreciable differences in the mechanical dimensions of the bench model and the actual cavities.

For the DORIS cavity, Q_{ext} values ranged from 300 to 10,000; for the CERN cavity, they ranged from typically $1.5 \cdot 10^4$ to $5 \cdot 10^6$; for the Cornell muffin tin cavity, they range from 800 to 44,000 (except for the "box modes", which are higher as previously mentioned); for the Cornell elliptical cavity, Q_{ext} values range (for 0 and 1 θ modes) from 700 to 780,000.

D. Fundamental Frequency

1. Determine Ability to Transfer Power to the Beam without Problems

The DORIS cavity transferred approximately 25 kW to the beam (4 X 8 mA) without problems. An initial power coupler window failure, caused by a water leak, did not recur after repair. In the CERN cavity test, up to 21 kW were incident upon the window at a beam current of about 10 mA; the input coupler had previously been tested up to 70 kW. No problems were encountered. In the Cornell muffin tin test, up to 12.5 kW was transferred to the beam by the cavities; the superconducting cavity put power into the beam, and the normal conducting cavity was used to take part of this power back out. This power was limited by an inappropriate adjustment of one of the interlocks; no problems with the input coupler were detected. Approximately 7 kW has been transferred to the beam so far in the KEK test; a window failure, apparently due to an insufficient flow of cold gas through the center conductor, was encountered.[7] These various powers need to be compared to the power requirement in the intended application; most are of the same order of magnitude, but a demonstration of full power handling capability would be desirable in those cases where it was not achieved.

2. Confirm Accelerating Field Calibration

Determination of the accelerating field in a superconducting cavity with heavy input coupling must rely on a calibrated reference probe, viewed through cables of known attenuation. This calibration must be established under conditions where the cavity is approximately critically coupled so that incident and reflected power can be used for an absolute field determination. In the Cornell muffin tin test, this calibration was checked in the beam by comparing it to values obtained from the synchrotron oscillation frequency and from the quantum lifetime of the beam. Total voltages measured this way were 1.58, 1.59, and 1.67 MV, respectively. No problems with this calibration were reported in the CERN, DORIS, or KEK tests.

3. Measure Heat Load vs Current on Resonance but Unpowered

In the KfK-CERN-DESY test of the DORIS cavity, the power deposited by the beam in the cavity both at resonance and anti-resonance was carefully measured. The measured power was slightly higher than predicted; no observed increase in cryogenic dissipation was reported with 88 watts of power deposited by the beam. Measurements on resonance were made in the CESR muffin tin test; it was found that the cryogenic dissipation at a given induced cavity field was twice the value found when the same field was produced by the klystron. It is believed that this difference was due to the difference in standing wave pattern in the input waveguide, and that the waveguide losses were anomalously high due to a failed weld in an LHe to LN_2 heat exchanger waveguide.

4. Measure Heat Load vs Applied Power with Cavity Off Resonance

This test provides a measurement of the losses associated with the input waveguide system. The interface between the superconducting surface and the normal conducting surface is a source of concern, since dissipation at this location ends up partially in the liquid helium. This measurement was not made in the Cornell muffin tin test, where the results would presumably have revealed the problem with the failed weld previously mentioned.

E. Controllability

1. Check Ability to Control the Field, Phase, and Tuning Angle

The only problems reported in this regard were in the CESR muffin tin test, where changes in the tuning angle stepping motor position caused microphonic changes in the cavity resonant frequency (this problem was alleviated by reducing the input coupling factor from Q_{ext} = 350,000 to 130,000 and by changing the shape of the stepping motor drive pulse), and in the CERN cavity test, where some of the tuning screws seized. No problems in the Doris cavity or KEK cavity tests have been reported.

2. Check Ability to Operate More Than One Superconducting Cavity Module Simultaneously

This study was made in the Cornell muffin tin test, and will be made in the DESY test and the Cornell elliptical test. With both modules powered by the same klystron, problems were encountered in the Cornell muffin tin test because of differences in the input couplings of the cavities (which, as mentioned, are mechanically sensitive because of the enhanced rejection of unwanted fundamental passband modes). In addition, it appeared that there may have been some coupling together of the higher order modes in the two modules via the common waveguide link; this can result in higher impedances than exhibited by either of the modules individually.

3. Evaluate Microphonics

Microphonics were presumably observed in the CERN cavity in the TM_{012} mode whose Q exceeded $5 \cdot 10^6$. Beam excitation of this mode fluctuated by 6 dB; this microphonic effect has been proposed as a possible way to limit the damage that a very high Q mode can cause, because the mode does not remain on resonance. The practicality of this proposal would depend on the frequency and amplitudes of the microphonics involved for a particular cavity, and on the growth rate and sources of damping for the instabilities of interest. In the CESR muffin tin test, as previously mentioned, microphonics were a nuisance for fundamental mode operation with Q_{ext} values in the hundred thousand range. The muffin tin cavity has 100 times the frequency sensitivity with bath pressure that the elliptical cavity of the same frequency and wall thickness has; it seems reasonable to assume that the ratio of microphonic sensitivities is similar. For the HOM's, the microphonic sensitivity of the muffin tin turned out to be a useful tool. Since the HOM damping rate is typically large compared to the microphonic angular frequencies, and since the microphonic angular frequencies are typically large compared to the beam damping rate, HOM's which are being driven by the beam follow closely the beam oscillation amplitude. HOM's which are microphonically being driven back and forth across a resonance, and are therefore likely to be the modes driving the resonance, vary in amplitude very much more than do the spectator modes. Without the microphonics, there is no way to distinguish the drivers from the spectators unless the impedance and frequencies of all modes are accurately known, and the coupling of these modes to a probe is also known.

F. Environmental Factors

1. Determine the Ability to Assemble a Complete System and Install It in a Storage Ring under Sufficiently Clean Conditions, and Without Introducing Other Limiting Factors

A difficult portion of a beam test is to assemble superconducting cavities to all of the necessary appendages (fundamental couplers, HOM couplers, reference probes, beam pipes, pumps, gate valves, etc.) under sufficiently clean conditions that the performance of the cavities is not degraded. A measure of how well we are succeeding in doing this is provided by looking at the best results obtained with various stages of assembly; it should be recognized that this table is misleading in two ways: more tests have been done at the earlier stages of assembly, yielding more opportunity for outstanding results; and the orders are not necessary chronological (exceptions to chronology are noted in the table). With these caveats in mind, it is believed that Table I provides a reasonable measure of our ability to avoid problems during installation. If it is assumed that the KEK cavity in the beam test could have gone to 4.2 MeV/m (it was operated at a lower field only as a conservative measure), and if the improvement obtained by baking the KfK cavity is taken into account, the four cases where cavities have gone from initial testing to final beam test have yielded beam test fields which were 72 to 78% of their initial fields. In at least two of these cases, specific causes of the degradation are known, as are methods of avoiding these degradations.

TABLE 1: E_{acc}, MeV/m

Laboratory	MHz	Cells	Shape	Full Structure Without Coupling Holes	Full Structure With Coupling Holes, Without All Couplers	Full Structure With All Couplers	Same, In Beam Test Cryostat	Same, In Beam
CERN	500	5	Spherical	-	2.7 (5.0)[a]	-	2.8	2.1
Cornell	1500	5	Muffin Tin	-	-	2.2 (3.6)[b]	1.9	1.7
Cornell	1500	5	Elliptical	-	-	15.3		
DESY	1000	9	Elliptical	7.0				
KEK	500	3	Spherical	-	5.8	-	4.2	3.5^+
KfK	500	1	Cylindrical	-	4.3	-	2.3	2.3 (3.15)[c]

a. Subsequent improved result, attributed to better chemical processing procedures. Original limitation is believed due to water residues.

b. Subsequent improved result. Previous results were limited by incomplete grooving in one module and an inside beam welding crack in two modules.

c. Subsequent improvement obtained by baking the cavity in situ.

Additional beam tests will provide more information on this very important question.

2. Study Tolerance to Gas Exposure

Some information on this question was provided by the "accelerated" exposure test conducted during the 1 year that a superconducting cavity was installed in the Cornell 12 GeV electron synchrotron. An exposure of $2 \cdot 10^{-9}$ Torr-years at each end of the cavity resulted in a 30% Q drop from its initial value of 10^9.[12] In this beam test, differential pumping normally provided a factor of 10^3 improvement in vacuum compared to the adjacent synchrotron. In the test of the muffin tin cavity in CESR, the Q_0 dropped by 13% during

12 days of operation with the gate valves open to the storage ring. The significance of this number is made questionable by the leak that was present (as previously discussed) between the cavity vacuum and the insulation vacuum. This was further aggravated by a leak from the liquid nitrogen shield into the insulation vacuum. During the Karlsruhe DORIS cavity test in PETRA, the cavity was accidentally let up to N_2 while at 80^0K; this lowered its Q_0 from 10^9 to 10^5, and lowered its E_{acc} from 2.3 MeV/m to 0.07 MeV/m. A one day bake at 50^0C raised its Q_0 to $1.5\cdot10^9$ and its E_{acc} to 3.15 MeV/m, more than recovering both its former Q_0 and former E_{acc}. In the CERN cavity beam test, the pressure at the cavity entrance varied from 10^{-8} to above 10^{-7} mbar, with the pressure normally closer to the lower value. After a few weeks, the Q_0 had dropped from 10^9 to $5\cdot10^8$. Warming up the cavity did not restore its original Q_0 value. The question is still open as to whether the Q_0 degradation was caused in this case by the vacuum exposure, chemical residues, radiation, or some combination of these factors. Depending on the outcome of further beam tests, it may be advisable to provide long-term installations with differential pumping or an extended LHe temperature beam pipe.

3. Study Problems with Dust

During the initial installation of the 11 cell muffin tin in the Cornell 12 GeV electron synchrotron, it was observed that there was dust in the synchrotron, and that this dust was capable of being transported, perhaps by electrostatic charging. An electrostatic precipitator was added, and no further evidence for dust problems was seen for 6 months. After this time, some upside-down sputter-ion pumps generated a large quantity of dust, part of which got past the precipitators and into the cavity, severely degrading its performance. The cavity was recovered by rinsing with detergent, water, and solvents, but no acids; original performance was restored in this way to the cavity, which was anodized. No problems due to dust were seen in the CESR muffin tin test; no electrostatic precipitators were used in this case. In the DORIS cavity test, the cold regions of the beam pipes were found to have a thin coating of low cohesivity material; this material readily turned to dust when disturbed. Although the source of this material is unknown, it is conceivable that it resulted from overheating of the elastomers in the gate valves, which occurred because the gate valves were not equipped with "trailers" to maintain a smooth bore when the gate valves were open. The beam test of the CERN cavity encountered no problems attributable to dust.

4. Determine Tolerance to High Energy Radiation

The test of the muffin tin cavity in the Cornell 12 GeV synchrotron established that no deterioration occurred due to exposure to more than 123 kRad of radiation. The radiation exposure in storage rings is likely to be significantly less than this in a decade because beam extraction and injection (when most spillage occurs) is done much less frequently than in a synchrotron. It was noted in the CESR muffin tin test, however, that turning off the normal conducting RF to dump the beam caused the superconducting cavity to break down; it is hypothesized that a portion of the 150 Joules of stored beam energy is deposited abruptly in the superconducting cavity, and that this energy is sufficient to raise the temperature above Nb's transition temperature at some location on the RF surface.

5. Determine Tolerance to Synchrotron Radiation

This measurement was made only in the KfK DORIS cavity test. 1.5 watts of synchrotron radiation were caused to strike part of the RF surface during cavity operation; no adverse effects were seen. The RF surface was always shielded from the synchrotron radiation in the CESR and CERN cavity tests. The DORIS cavity measurement is of importance because, at very high electron energies, there will be substantial amounts of scattered synchrotron radiation which cannot be effectively masked.

6. Measure the Static Heat Leak of the Cryostat

The static heat leak of the Cornell cryostat was 4.5 watts at $2.3^{o}K$, of the KfK cryostat was 6 watts at 1.8 to 4.2°K, and the heat leak of the CERN cryostat was 10 watts at 4.3°K. The heat leak of the KEK cryostat is 12 watts. All of these heat leaks are less than the expected RF dissipation.

G. Reliability

1. Determine Effectiveness of Interlocks in Protecting the Cavity

In all beam tests conducted to date, the interlocks have served to prevent any damage to the cavity as a result of cavity breakdown. In the KfK DORIS test, breakdowns were accompanied by a loss of 10 liters of LHe; perhaps this was caused by the the heavy coupling of the input coupler, which had $Q_{ext} = 40,000$. In the CESR muffin tin and KfK DORIS cavity tests, when the interlocks turned off the superconducting cavity, they also turned off the normal conducting cavities to dump the beam and prevent the beam from depositing power into the superconducting cavity's fundamental mode while part of the surface was normal conducting. The CERN cavity controls and interlocks had the very nice feature that, instead of turning off the normal conducting cavities and dumping the beam, the superconducting cavity was quickly tuned off resonance to avoid beam heating. After a matter of seconds, the cavity was turned back on and brought back to resonance. This feature would be extremely desirable in a ring equipped with a large number of superconducting cavities so that a breakdown in one cavity would not cause the beam to be lost.

2. Evaluate System Reliability

The system reliability can best be evaluated in terms of the problems encountered, and the ease or difficulty of finding solutions to these problems.

In the Cornell CESR muffin tin test, one problem was icing of external pipes, which jammed mechanical mechanisms and destroyed electronics when the ice melted; this can be corrected by adding regulated heaters to the pipes, and by routing them so that they do not pass over water-sensitive equipment. A second problem was that a blower pump shaft broke; the probability of this could be reduced by using newer pumps, or by operating at 4.2°K so that such pumps are not needed.

A third problem was that helium system pressure oscillations occurred at about 1 and 25 Hz; this could be corrected by controlling the heat capacity, heat exchange rate, and impedance of lines involving temperature gradients; it was controlled by adding large buffer volumes to the line outside the cryostat. A fourth problem was that a stainless steel elbow developed a leak through its wall, leaking LN_2 into the insulation vacuum; a more thorough leak checking procedure might have uncovered this problem. A fifth problem was that an ion pump used to pump on the waveguides between the LHe and 300^oK windows on the HOM waveguides and on the waveguides between the LN_2 and 300^oK windows on the fundamental waveguides exhibited a periodic pressure instability; this is being corrected by substituting a triode pump for the diode pump previously used. A sixth problem was that two indium joints leaked; this situation is being improved by using thicker flanges, and taking greater precautions that they are flat, unscratched, and that the bolts remain under tension as a function of temperature. A seventh problem was that the tuner motors were initially frozen, and were broken free by repeated cycling; this situation could be improved by longer pumping cycles to evaporate any residual water, and by operating the tuners during cooldown to break up any freezing material as soon as it formed. An eighth problem was that of microphonics; isolation of the stepping motor from the tuning mechanism on muffin tins, or use of the more rigid elliptical or tapered end wall spherical cavities should alleviate this problem. A ninth problem was that the cavity coupling was too sensitive to small dimensional changes; without giving up the enhanced damping of unwanted modes in the fundamental passband, reinforcement of the coupler with braces and use of a motorized coupling adjuster provide solutions. A tenth problem was that the Q_0 of one of the two modules was less than 10^9; it is presumed that this was caused by the torn weld in the waveguide heat exchanger near where this heat exchanger meets the Nb input waveguide of the cavity. It is believed that this weld tore because the heat exchanger partially collapsed, which in turn occurred because of atmospheric pressure loading. This problem will be attacked by using springs to keep the waveguide heat exchangers under tension.

In the KfK-CERN-DESY collaborative test of the DORIS cavity in PETRA, one problem was heating of the contact between the HOM couplers and the cavity; this was improved on later models by moving the location of a high current weld, and by using a bellows in place of a contact joint. A second problem was the overheating of the elastomers in the gate valves; this could be eliminated in the future by using "trailers" to present a smooth impedance to the beam when the gate valves are open. A third problem was the formation of the material, previously described, on the walls of the cold portion of the beam pipe; if this material did not originate from the overheating of the gate valve elastomers, no procedure for preventing its recurrence is known. A fourth problem was damage to the input window caused by a water leak in this region; improved construction should eliminate this problem. A fifth problem was the extreme mechanical sensitivity of the HOM couplers with regard to rejection of the fundamental; this problem has been alleviated by making these couplers remotely tuneable.

In the CERN test in PETRA, one problem encountered was that of LHe leaks in lead joints; this will be attacked by using fewer joints. A second problem was the isolation of some TM_{012} passband members to a small number of cells; this will be attacked by using a new geometry.[10] A third problem is that of field enhancements and induced multipacting due to holes in the cell walls; the possibility of avoiding this problem by using beamline couplers is being explored. A fourth problem was that two cells developed lower field breakdown locations than had originally been present; it is believed that this problem has been corrected by using improved chemical cleaning methods (as demonstrated by achieving 5.0 MeV/m in the structure). A fifth problem was that, as previously discussed, the Q dropped irreversably from 10^9 to $5 \cdot 10^8$; both better chemical cleaning and improved beamline vacuum may be tried as a cure for this problem. A sixth problem was that 200 monolayers of gas were desorbed when the cavity was warmed up; this quantity of gas seems anomalously high for the pressures to which the cavity was subjected while cold; the origin of this gas is not fully understood. A seventh problem, as previously discussed, was that large stained areas containing P, K, and Ca were found in the cavity; it has been concluded that better chemical processing measures need to be taken to avoid this problem. An eighth problem, as previously discussed, was that some of the tuner adjustment screws siezed; it is planned that this problem be eliminated by tuning the cavity hydraulically from the ends.

In the KEK cavity test in the KEK accumulator ring, one problem was that two higher order mode ceramics failed during cooldown; a third replacement appears to be satisfactory. A second problem was that the power coupler window failed, as previously mentioned, from having its cold helium gas flowing at too low a rate; this flow rate will be corrected before the test continues.

Although each of the beam tests in storage rings encountered a number of problems, it is encouraging that none of the problems was serious enough to prevent the cavities from being used to store a beam, and that proven or promising solutions have been found for most of these problems.

III. Future Beam Tests

The beam tests which have been completed have provided ample evidence of the suitability of superconducting cavities for use in electron storage rings. Remaining beam tests will presumably provide similar information concerning the particular structures being tested.

One desirable objective of future beam tests would be to perform the tests under conditions where instabilities exist (but not by raising Q_{ext} values of HOM's artificially); thresholds could then be compared to theory, and, with the theory verified, predictions made of the thresholds in the machine in which the cavities are eventually to be used.

Another desirable objective would be to test the cavities under conditions where the higher mode power coupled out of the cavity equals that in the intended application, and the power coupled into the beam equals that in the intended application.

In view of the questions which have arisen in regard to contaminants found in the cavities after the beam test, it would be desirable to have dust-free non-contacting periscopes available for inspecting the interiors of the cavities after final processing and before use. This entails some risk to the cavity, but the information is important.

Further measurements need to be made, perhaps with smaller cavities connected to but not in series with the beam line, to determine the correlation between beam line vacuum and cavity performance deterioration.

Finally, it is desirable (but a very major undertaking) to test full scale modules, optimized for cost, reliability, and ratio of active to total length. These would serve as prototypes for the final machine application.

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