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HIGH GRADIENT SUPERCONDUCTING CAVITIES FOR STORAGE RINGS*

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Abstract

Superconducting (SC) cavities for use in electron storage rings have advanced to the point where several laboratories are making definite plans to use them on a large scale. Laboratory tests of multi-cell SC cavities, including input and higher-order-mode (HOM) couplers, have yielded accelerating fields up to 15.3 MeV/m (CW). Reasons for the improved performance are discussed. Since the 1983 International Accelerator Conference in August, 1983, four SC cavities have been tested in storage rings. The cavities have yielded accelerating gradients up to 6.5 MeV/m, in excess of the frequently-quoted objective of 5 MeV/m. In addition, the average gradient obtained in these four tests was 4 MeV/m, almost twice the average obtained in the four cavities tested in storage rings during 1982 - 1983.

Introduction

Recent improvements in SC cavities for storage ring service are based, in large part, on work that has been done with single cells, as reported in the previous paper by H. Piel [1]. In addition to the application of SC cavities to storage rings, considerable use of such cavities for ion acceleration is occurring as reported, for example, in the following paper by K. Shepard [2]. SC cavities are also finding application in recirculating linear accelerators [3, 1].

Planned Applications of SC Cavities to Electron Storage Rings

Plans are being made for the large-scale application of SC cavities to electron storage rings. Some of these plans are preliminary, and others are quite advanced. All represent a recognition that the use of SC cavities is the most practical method to reach electron storage ring energies of 30 GeV or greater. These plans are listed in Table I.

At CERN [4], SC cavities will be included with NC cavities in LEP I as a test of the SC cavities. In LEP II, SC cavities would be used by themselves to reach the W production energy and higher.

At DESY [5], SC cavities are planned for inclusion in the HERA electron ring as a means to supplement the NC cavities, reach the design energy and current simultaneously without building new NC cavities, to save electrical power, and to minimize the transverse impedance of the machine.

At KEK [6], SC cavities are planned for installation in TRISTAN in two phases, each resulting in a higher energy than can be reached with NC cavities.

Laboratory	Storage Ring	Energy, GeV	Freq., MHz	Cells per Cavity	Cavities	E(acc), MeV/m	Q, *1E-9
CERN	LEP I	55-62	352	4	8 - 16	5 - 7	3
CERN	LEP II	95-104	352	4	384	5 - 7	3
DESY	HERA e	30	500	4	16		
KEK	Tristan	33-35	508	5	40		
KEK	Tristan	40	508	5	120-144		

TABLE I. Plans for the application of SC cavities to storage rings.

Requirements for SC Cavities for Use in Electron Storage Rings

SC cavities used in electron storage rings have a number of requirements which are challenging compared to the requirements for normal-conducting (NC) cavities for the same application: (1) accelerating fields of at least 3 MeV/m are typically required to make the added complexity of the SC cavities worthwhile compared to the 1.0 to 1.7 MeV/m at which NC cavities are operated in storage rings; (2) Q-values in excess of $5*10^8$ are required to compensate for the refrigerator ineffiency for SC cavities, making exceptional cleanliness mandatory; (3) unloaded Q-values of HOM's are typically $3*10^4$ in NC cavities, and $1*10^9$ in SC cavities; the first number is sufficiently low to prevent cavity-induced multi-turn instabilities for well separated bunches, whereas the second number is not, thereby requiring development of HOM damping schemes for SC cavities; (4) copper NC cavities can be processed through strong multipacting barriers by applying sufficient power, whereas SC cavities must have a geometry such that any multipacting barriers are weak; (5) surface magnetic field enhancement in SC cavities must be kept small to avoid exceeding the local critical field, thereby further restricting the geometry; (6) the surface electric field enhancement in SC cavities must be kept small to keep dissipated power due to field emission from becoming excessive; (7) the cavity geometry must be suitable for rinsing after chemical cleaning, eliminating designs having inside cracks and regions which do not drain liquids effectively; (8) the beam aperture in a SC cavity is commonly made exceptionally large in order to reduce the transverse impedance, capable of inducing the fast head-tail instability; (9) the input coupling structure of a SC cavity must be capable of handling the power input to the beam without causing excessive heat dissipation at liquid helium temperature; and (10) the tuning mechanism must be capable of keeping the cavity on resonance, which is significantly more difficult for a SC cavity because the bandwidth is much narrower than in a NC cavity. Designs exist which meet all of these objectives.

Laboratory Tests of Storage Ring Cavities

Eight SC cavities designed for electron storage ring service have been tested in the laboratory since the August 1983 International Accelerator Conference; the results of these tests are presented in Table II. As noted in the table, some of the cavities were tested with coupling ports not yet installed on the cavity, some were tested with coupling ports installed but without the couplers, and some were tested with the couplers installed; each such device which is added obviously increases the chance for problems due to defective welds, unfavorable geometries, overheating of NC components, and introduction of dirt.

The CERN 500 MHz cavity [7] listed in Table II uses cell wall penetrations for input and HOM couplers, whereas the CERN 352 MHz cavity [8] uses beam pipe couplers for these purposes. Both cavities are "spherical" cavities [9] in that their longitudinal profiles are described by circular arcs. They are cylindrically symmetrical about the beam axis. The couplers are coaxial.

The Cornell 1500 MHz cavities are "elliptical" because their longitudinal profiles are composed of elliptical segments [10]. Each cavity has an input power waveguide coupler intersecting the beam pipe at one end, and two HOM power waveguide couplers intersecting the beam pipe at the other end. Two of these cavities are shown in Figure 1.

The DESY 1000 MHz cavities [11] are of the "elliptical" design, and use one input power waveguide coupler intersecting the beam pipe at one end, and one HOM power waveguide coupler intersecting the beam pipe at the other end. The tests reported in this table were made before the couplers were welded to the cavity.

The KEK 508 MHz cavity [12] is of the "spherical" design, and uses coaxial fundamental and HOM couplers penetrating the cell walls. This cavity is shown in Figure 2.

Note that all eight of the cavities listed in Table II yielded accelerating gradients equaling or exceeding the commonly-quoted goal of

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Lab	Year	MHz	Cells	Emax MeV/m	Q @ E *1E-9	MeV/m	Coupling holes	Couplers	Limitation
CERN	1983	500	5	5.0	0.74	5.0	Yes	No	Defect, main coupling hole
CERN	1985	352	4	6.0	3.3	5.0	Yes	No	
Cornell	1984	1500	5	8.9	7.	8.9	Yes	Yes	Defect, location undetermined
Cornell	1984	1500	5	8.0	3.	8.0	Yes	Yes	Defect, cell 3, 2.5 cm from eq.
Cornell	1984	1500	5	15.3	2.	15.3	Yes	Yes	Defect or field emission, cell 1
DESY	1983	1000	9	6.6	0.9	6.6	No	No	Defect or electron loading
DESY	1983	1000	9	>6.7	0.9	6.7	No	No	Available power
KEK	1983	508	3	>5.2	0.5	4.0	Yes	No	Available power

TABLE II. Laboratory results on multi-cell cavities designed for storage ring use.

5 MeV/m, with values as high as 15.3 MeV/m. All of the Q's reached in these tests would be tolerable values, although improvements would obviously be beneficial. The second, fourth, and fifth cavities listed in this table are made of improved thermal conductivity material, which enhances the cavity's ability to tolerate localized defects without quench [13].

Reasons for Improved Cavity Performance

Significant improvements in the performance of SC storage ring cavities during the last several years are attributable to a number of factors.

The adoption of spherical and elliptical shapes by all laboratories developing SC storage ring cavities has eliminated strong multipacting barriers, which barriers were serious impediments to increases in the fields achieved in SC cavities for many years.

Couplers which couple to the beam pipe, rather than penetrating the cell walls, are now preferred. Cell wall penetration could still be necessary where extremely strong HOM damping is required.

The use of electron beam welding parameters which do not cause a vapor column to penetrate the niobium during welding are important in avoiding regions of the weld which do not break down at an anomalously low magnetic field. It appears that the use of the vapor column, which is standard beam welding practice, causes vacuum voids near the surface which disrupt the heat conduction path. Use of a "rhombic raster" beam welding parameter [14] or use of an electron beam defocussed in a controlled manner [15] both avoid this problem.

Improvement of the thermal conductivity of the niobium is accomplished by reducing the interstitial impurities, particularly H, C, N, and O [13]. This is accomplished by electron beam melting Nb more slowly and more times in a better vacuum than is customary, and by taking precautions to prevent recontamination of the Nb during rolling. Further purification using a sublimated film of Y[16] or Ti[17] has

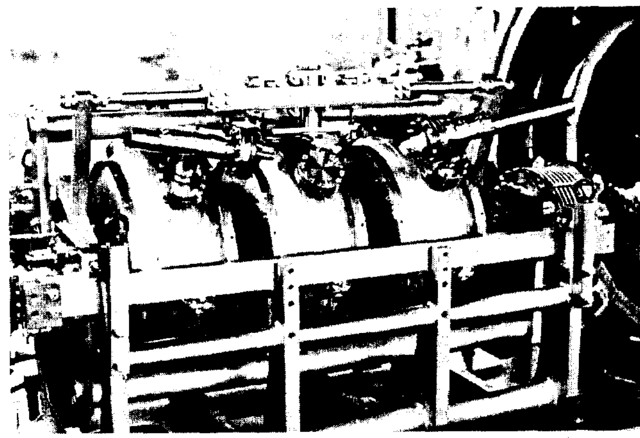

FIGURE 2. KEK 3-cell, 508 MHz SC cavity, with couplers.

proven successful. The improved thermal conductivity increases the heat that can be dissipated in a localized defect without driving the surrounding Nb above its transition temperature.

Surface inspection procedures have been improved. The Nb is anodized and inspected for surface defects; any suspected defects are ground away, reducing the probability of a defect at or near the surface.

The speed with which the cavities are rinsed with demineralized water after being chemically cleaned has been increased, reducing the risk of chemical residues being left on the surface.

Cavities are being attached to their test stands in dust-free enclosures to reduce the probability of dust entering the cavity during mounting. Dust lowers the Q, enhances field emission, and can act as a breakdown nucleation point.

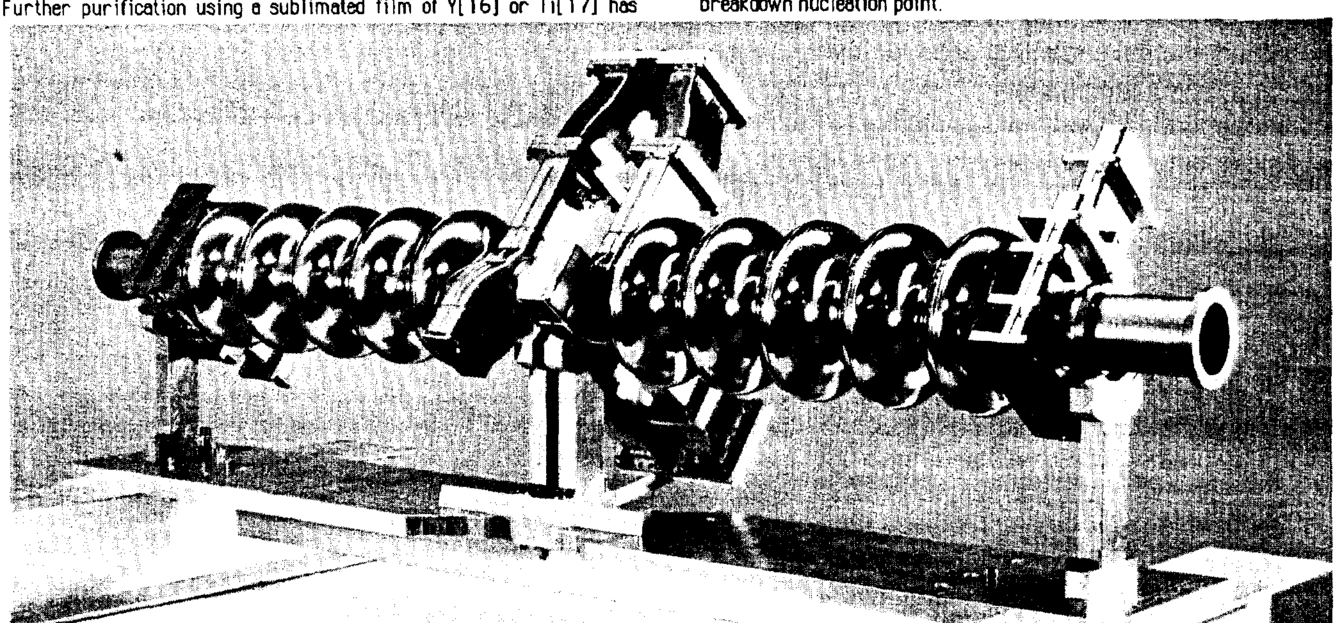

FIGURE 1. Two 5-cell 1500 MHz Nb cavities, with couplers.

Beam Tests Conducted Since August 1983

Three beam tests have been conducted [12, 5] since the last International Accelerator Conference, as listed in Table III. The test at Cornell simultaneously tested two separate cavities installed in the same cryostat. The cavities tested in these beam tests are among those listed in Table II. All cavities in these tests were equipped with fundamental power and higher order mode couplers. In the DESY test, the operating temperature is 4.2°K, and the BCS Q of the cavity is $0.8*10^9$[5]. In the Cornell test, both cavities exhibited nearly the same Q; it was determined that the measured Q of $1.6*10^9$ consists of a BCS Q of $5.13*10^9$ (2.3°K), an effective Q due to the input power coupler (dissipation, with heat leakage into the liquid helium) of $4.83*10^9$, and a residual Q of the cavity itself of $4.51*10^9$. Also, in the Cornell test, the cavity which supported 6.50 MeV/m did not show any appreciable reduction of Q as the field was increased from 2.1 MeV/m to a value slightly below breakdown.

The maximum beam current in the KEK test was limited by the absence of an aperture-matching "trailer" in the gate valves, leading to heating by HOM's of the gate valves. In the Cornell test, the maximum current was limited by beam instabilities. In the DESY test, the maximum current is believed to be limited by instabilities caused by the NC cavities in the ring. The maximum power transferred to the beam in the KEK test was limited by heating of the input power coupler, in the Cornell test by beam instabilities, and in the DESY test by arcing in the waveguide caused by an oversight (not all of the waveguide ridge edges were radiussed).

The KEK beam test cryostat is shown in Figure 3, the Cornell cryostat in Figure 4, and the DESY cryostat in Figure 5. The DESY cryostat is designed to accommodate two nine-cell cavities.

One of the most significant efforts in developing SC cavities for storage rings is involved in determining what HOM damping is required to achieve beam stability and in developing couplers to achieve that damping. The distribution of loaded Q values of HOM's measured during the Cornell beam test is shown in Figure 6. These values are determined by fitting a Lorentzian, superposed on a flat background of unknown phase, to the beam spectrum measured on a spectrum analyzer. The measured values are consistent with values measured in bench models.

In the KEK beam test, a very thorough measurement of HOM's and their effects on instabilities was made. The frequency of each important HOM was measured as a function of tuner position, and each HOM, where possible, was tuned to a frequency where it produced the maximum instability driving force. A vertical instability was observed due to one of the deflecting modes, at a current slightly higher than the expected threshold. In the Cornell beam test, the tune of each cavity was shifted in 400 equal increments, and the instability threshold current was measured for each of these tuner positions; an approximate probability of instability vs. beam current was thus measured by this procedure. The expected instability probability vs. beam current was determined using a computer code developed by R. Siemann [18]. The measured and computed instability probability curves are in good agreement, as shown in Figure 7; the measurement for the other cavity showed a somewhat higher slope, but was also in reasonable agreement

Cavities operated in Storage Ring Beams since August 1983				
Laboratory	KEK	Cornell	Cornell	DESY
Storage ring	Accum.	{ CESR }		PETRA
Year	1984	{ 1984 }		1985
MHz	508	{ 1500 }		1000
Cells	3	5	5	9
E(max), MeV/m	4.3	6.50	2.41	2.64
Field limitation	Input coupler	Field emission (?)	Defect	Defect (?)
Q * 1E-9	0.8	{ 1.60 }		0.69
@ E, MeV/m	3.7	{ 2.1 }		1.7
HOM power, W	≥ 45.8	{ 282 }		
Max. beam, mA	10	{ 22.7 }		9
Max. power into beam, kW	4	{ 26.6 }		26

TABLE III. Results of recent storage ring beam tests.

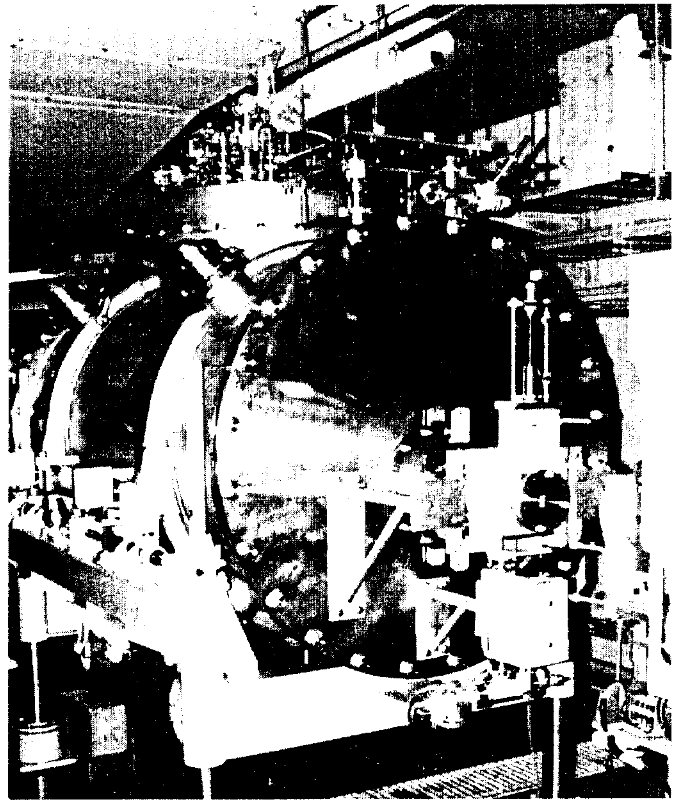

FIGURE 3. KEK cryostat, 1984 beam test.

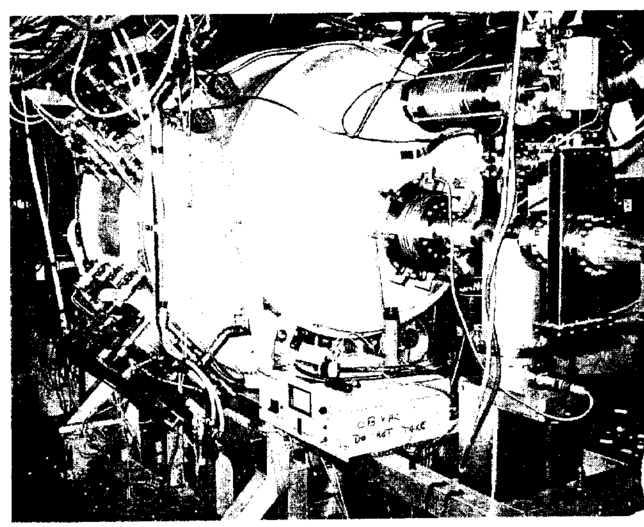

FIGURE 4. Cornell cryostat, 1984 beam test.

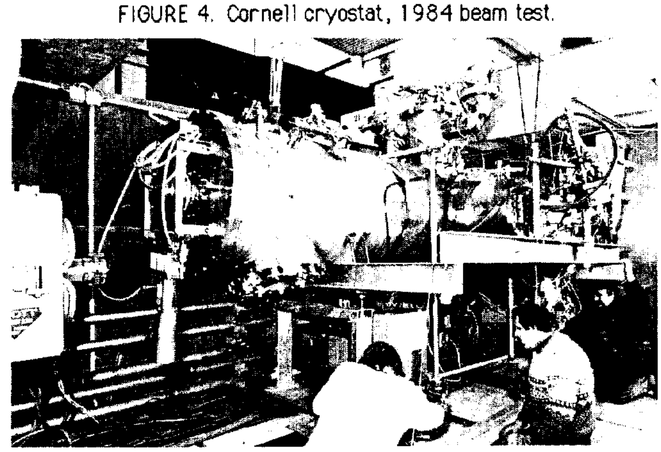

FIGURE 5. DESY cryostat, 1985 beam test.

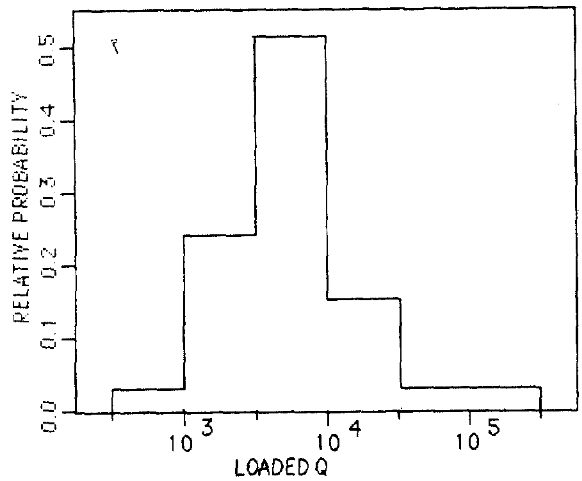

FIGURE 6. Measured probability distribution, loaded Q's.

with the theoretical curve. In the DESY beam test, the Q and power associated with each HOM is being measured for comparison to bench measurements and calculations.

In the Cornell beam test, a coherent dipole vertical instability was encountered at 0.91 mA. It has been shown [19] that quadrupole and higher order transverse instabilities are highly and preferentially suppressed by the curvature of the RF waveform. The dipole instability was then suppressed by feedback, using a coil around a metallized vacuum chamber. A longitudinal dipole instability was next encountered at 1.4 mA; addition of Robinson damping raised this threshold to 5 mA. Application of longitudinal feedback through modulation of the RF phase, combined with a slight shift in the tune plane, raised the instability threshold to 22.7 mA. Further gains were difficult because instabilities arising at this current caused very rapid beam loss, making diagnosis difficult.

No measurable decrease in the breakdown fields were measured in the Cornell beam test as a function of beam current, indicating that the HOM-induced fields in the cavity were small compared to the fundamental mode fields.

No problems were encountered in the Cornell beam test associated with the simultaneous operation of two SC cavities.

The fields obtained during the beam test in one of the Cornell cavities and in the DESY cavity are appreciably lower than those obtained in laboratory measurements. In the Cornell cavity, the lower field is believed to have been due to a defect in the third cell, at the equator, and at the bottom of the cavity. The cavity was chemically cleaned between the two tests, so it cannot be ascertained whether an inclusion was uncovered by the chemical treatment, or a foreign object entered the cavity; the location of the defect is consistent with a foreign object.

The understanding of charged dust transport in storage rings has greatly improved [20], and methods for keeping such dust from entering storage ring cavities have been devised [21, 20].

Conclusion

The prospects for successful application of SC cavities to electron storage rings appear to be excellent. Three laboratories have made plans to use SC cavities for this purpose. All of the recent laboratory tests of multi-cell storage ring cavities have yielded accelerating gradients between 5.0 and 15.3 MeV/m. Beam tests of 4 cavities in storage rings during the past 21 months have yielded average accelerating fields of 4.0 MeV/m, compared to 2.2 MeV/m for the 4 cavities tested in storage rings during the preceding 17 months [22]. The commonly accepted objective of achieving 5 MeV/m in a storage ring has been surpassed, with an accelerating field of 6.50 MeV/m. Measured Q's have also been quite acceptable. Measured instability thresholds indicate that the tested cavities have HOM damping which is more than adequate to prevent multi-turn instabilities in the machines for which they were developed. By improving cleanliness during assembly of cavities for installation in storage rings, and by improving the cleanliness of the storage rings themselves, there appears to be no

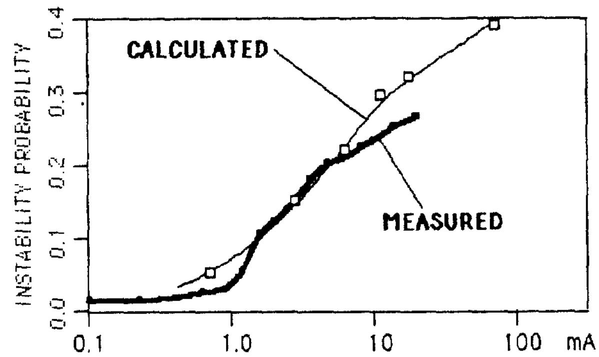

FIGURE 7. Calculated and measured instability probabilities.

reason why the laboratory field of 15.3 MeV/m cannot be reached on occasion in a storage ring, nor why the objective of 5 MeV/m cannot be reached on a regular basis. Extensive work to investigate this question is planned in the near future at CERN [15], and long-term tests involving SC cavities installed in or connected to the vacuum of storage rings are under way at DESY[5] and KEK[6].

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