HIGH GRADIENT TESTS OF 1.3 GHz SUPERCONDUCTING CAVITIES

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Abstract

Once breakdown had occurred at an accelerating gradient of 11 ~25 MV/m, a common phenomenon resulting in Q_0-deterioration due to field emission was observed in every cavity test. This problem has been settled by removing a ceramic disk which was used to support an antenna of a movable input coupler. With this improvement, an accelerating gradient of 30 MV/m with a high Q_0 value of 1.0×10^{10} has been reproducibly achieved in three single-cell cavities which were treated by the standard surface preparation techniques at KEK.

Introduction

The development of high gradient superconducting cavities is essential for their applications in future accelerators, such as FEL drivers, proton LINACs for neutron sources and TESLA (TeV Energy Superconducting Linear Accelerator). In the case of the TESLA application, an accelerating gradient of higher than 25 MV/m with a Q_0 value of more than 5×10^9 is required [1]. To realize this performance and so to study high gradient phenomena, the development of 1.3 GHz niobium superconducting cavities was started in 1991 at KEK. An experimental hall was built for this purpose. A clean room (class 10) for assembly and a vertical cold test stand including a helium pumping system and an rf measurement system were constructed. Several single-cell cavities and two nine-cell cavities were fabricated at CEBAF, MHI and KEK. A vacuum furnace for high temperature heat treatment (HT) at 1400°C, a high pressure water rinsing system with 85 kg/cm^2 ultrapure water and a temperature mapping system consisting of 684 carbon thermometers were developed.

In a series of cavity tests carried out until Dec. in 1993 [2], it became clear that field emission was not the main obstacle limiting the maximum accelerating gradient (Eacc,max) and the standard procedure established in the TRISTAN superconducting cavities looked good enough to achieve an accelerating gradient of 25 MV/m. However, one serious problem encountered was the fast breakdown and the resultant Q_0-deterioration due to field emission. After some trials, it was found out that a ceramic disk attached at a movable input coupler was concerned in the Q_0-deterioration. By removing the ceramic disk, the cavity performances were remarkably improved and the Q_0-deterioration was eliminated.

The phenomenon of the Q_0-deterioration after breakdown and the recent cavity performances without the ceramic disk are reported in this paper. A DC breakdown experiment using niobium electrodes to understand the phenomenon is reported as well.

Q_0-deterioration after Breakdown

No field emission had been observed during the initial Q_0 - Eacc scan, but the Q_0 values begun to deteriorate after breakdown. The typical feature of this phenomenon is shown in Fig. 1. The breakdown was usually accompanied with the vacuum deterioration and x-ray emission, and it occurred in the field range above 11 MV/m. In the temperature mapping, any obvious heating site above sensitivity did not exist before the Q_0-deterioration, but some remarkable temperature rises in the vicinity of the iris were observed after the Q_0-deterioration. These heating sites changed to clear ridge lines with increasing input rf power. RF processing in the strong field emission region caused degradation of the Q_0 values even at a low field, namely, it led increment of the residual surface resistance. The field enhancement factor (β) obtained by Fowler-Nordheim plots was between 200 and 450. After the Q_0-deterioration, surface removal of more than 15 μm was necessary in order to recover the performance. Similar phenomenon has been observed in all the tests, independently on a cavity shape (spherical or elliptical), a niobium material (RRR = 100 ~350), a surface treatment (CP or EP) and an

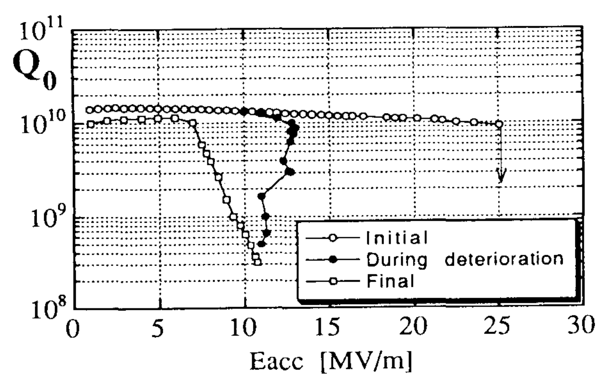

Fig. 1 The Q_0 values were gradually degraded after breakdown at the maximum gradient in the initial measurement. Finally, strong field emission was observed at the lower fields.

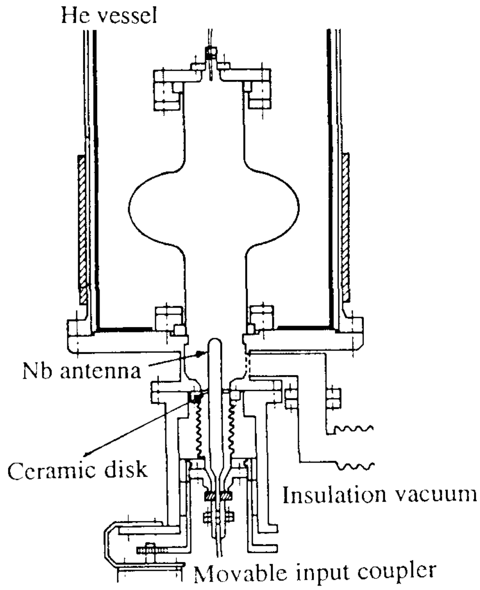

Fig. 2 The vertical cold test system.

antenna material of an input coupler (Nb or Cu).

From the experimental fact as mentioned above, it is supposed that sparking might have occurred somewhere inside the cavity. Two hypotheses about the cause of sparking are considered. One is that microstructure such as protrusions, cracks, scratches, pits or grain boundaries existing at a high surface electric field in the cavity may contribute to the initiation of sparking. This idea motivated us to investigate the DC breakdown field strength of niobium electrodes (see later section). Another is that sparking may occur at couplers, flanges or joints equipped to a cavity. Their edges and surfaces had been made smoother, but the effectiveness did not appear. Careful inspection of the vertical test stand suggested that the most doubtful component causing sparking seemed to be a ceramic disk supporting an antenna of a movable input coupler, although an electric field is very low at the location of the ceramic disk. The vertical cold test system is illustrated in Fig. 2.

As described later, the successful results after removing the ceramic disk prove that the ceramic disk is responsible for this phenomenon. It is supposed that charging up by field emitted electrons is a trigger of sparking.

Recent Cavity Performances

Some improvements in the diagnostic systems were made to understand this phenomenon. Since the scanning time of the temperature mapping system is about 20 seconds, it is very difficult to detect the temperature rises on real time during breakdown. In order to detect a fast phenomenon continuously, the bridge circuits with four ports and chart recorders were employed instead of the scanner and computer. Sixteen carbon thermometers were attached at the upper and lower iris in the cavity. Sixteen PIN-photo diodes covered with a lead collimator were mounted at the same location as the thermometers to monitor x-ray emission.

After removing the ceramic disk, eight vertical cold tests have been carried out on three single-cell cavities of C1, C3 and K1, and the test results are summarized in Table 1. Distribution of the attained Eacc,max is shown in Fig. 2 in comparison with that before removing the ceramic disk. The typical Q_0 - Eacc plots for the C1, C3 and K1 cavities is shown in Fig. 4. The C1 and K1 cavities had been tested several times with the ceramic disk, and heat treatment at 1400°C had been performed before. These previous test results (until 1993) are discussed in detail in reference [2], and one of the results on the C1 cavity is shown in Fig. 1. The C3 cavity is a virgin cavity, and only 760°C annealing for hydrogen degassing was carried out. Final polishing of 20 ~50

Table 1.
Test results after removing the ceramic disk.

cavity	test	HT at 1400°C	Rres [nΩ]	Eacc,max [MV/m]	limitation	x-ray detection
C 1	I	yes	9.6	31.5	breakdown	no
	II		8.3	30.2	breakdown	weak
	III		21.4	30.7	breakdown	no
	IV		9.7	28.7	breakdown	no
C 3	I	no	6.2	33.0	self-pulsing	strong
	II		5.0	31.3	rf power (f.e)	strong
K 1	I	yes	10.9	28.6	breakdown	weak
	II		34.6	19.0	self-pulsing	strong

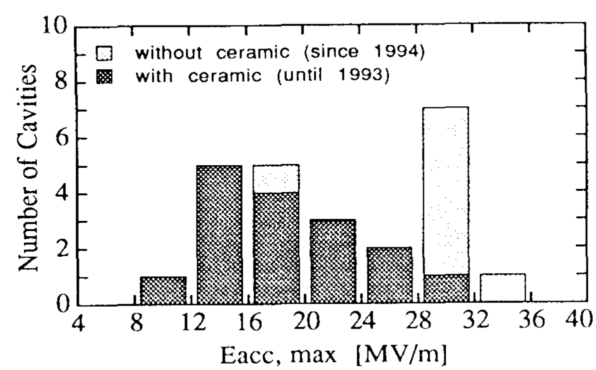

Fig. 3 Distribution of the maximum accelerating gradient before and after removing the ceramic disk.

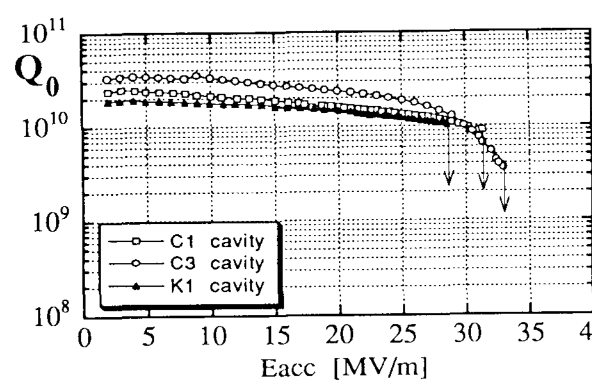

Fig. 4 Q_0 - Eacc plots for three single-cell cavities after removing the ceramic disk.

μm was usually performed by CP except the K1 -II test (EP), and additional surface treatment was not carried out in two tests (C1 -III and -IV). Total amount of removal by surface treatment reached to 200 ~300 μm in each cavity. High pressure water rinsing was always carried out.

The Eacc,max of about 30 MV/m was routinely obtained as shown in Table 1, and the rf power loss on the cavity surface was about 12 W at 30 MV/m. It is worth to notice that an Eacc,max of higher than 30 MV/m was achieved even in the C3 cavity with no heat treatment at 1400°C. In the C1 -III test, the cavity had been left for 22 days without pumping after the previous test, but no degradation of the performance was observed. The limitation of the Eacc,max is considered to be thermal breakdown in every test except C3 -II, because temperature rises synchronized with the breakdown were detected and the time constant of dissipation of stored energy was usually 0.5 ~1 msec. Though the effort to push up the Eacc,max were made many times, the breakdown gradient did not change and the Q_0-deterioration was not observed. Weak x-ray emission was detected at the high gradient in two cases, but drop of the Q_0 values was not observed because of slight electron loading. When strong x-ray emission was detected, self-pulsing (periodical breakdown) was observed in two test. The cycle was 0.5 ~1 second, and considerable temperature rises were observed during breakdown.

The residual surface resistance (Rres) obtained in each test was a fairly low value of 5 ~11 nΩ except two cases. Trapping of the residual magnetic flux (~10 mG) during cooldown and rf losses at the end of the cutoff tubes are considered to be the main component of the Rres. The installation of the temperature mapping system, which has magnetized parts (springs), seems to be the reason for the large Rres in the C1 -III and K1 -II tests, and the contribution of about 10 nΩ is estimated experimentally. The remaining fraction might be the influence of hydrogen.

The resonant frequency of the cavity is shifted by the deformation due to the vapor pressure of liquid helium or the Lorentz force action of the electromagnetic field to the surface currents. The resonant frequency was linearly increased with pumping down of liquid helium, and about 150 kHz was shifted by the change from 760 Torr (4.2 K) to 12 Torr (1.8 K) ; *i.e.*, 200 Hz per Torr. The frequency shift due to the Lorentz force was proportional to a square of the accelerating gradient, and the resonant frequency at 30 MV/m became about 5 kHz lower than that at a low field : *i.e.*, 5.5 Hz per $(MV/m)^2$. These results require the reliable stiffening schemes in a pulsed operation to reduce the effect of the deformation.

DC Breakdown Experiment

Experiments to study vacuum discharge of niobium electrodes at room temperature have been initiated in collaboration with Saitama University. The experimental system and the experimental procedure are described in reference [3]. A pair of niobium electrodes are set in the vacuum chamber with a vacuum pressure of 1.0×10^{-10} Torr. The gap distance between electrodes can be adjusted between 10 mm and 0.3 mm. The impulse voltage applied to the gap has a rise time of 60 μsec, a decay time of 700 μsec and a peak value of 100 kV. The energy of several joules is dissipated at the electrodes during breakdown, and this energy is comparable to the energy stored in the cavity at a high gradient. The DC voltage is possible to apply up to 50 kV.

The surface treatment of samples was carried out by machining (lathe), CP or EP, and heat treatment at 1400°C was applied in two samples. The average surface roughness (Rz) of each sample was 2 μm in machining, 3.5 μm in CP and 0.5 μm in EP. Six niobium samples have been tested, and the breakdown field strength is shown in Fig. 5. First breakdown fields of 40 ~80 MV/m were obtained except one test, and this is considerably high in comparison with a value around 20 MV/m on copper electrodes. The second breakdown field deteriorated remarkably in three tests. In order to discuss the characteristic of the test results, it is necessary to accumulate statistics and reproducibility for more samples.

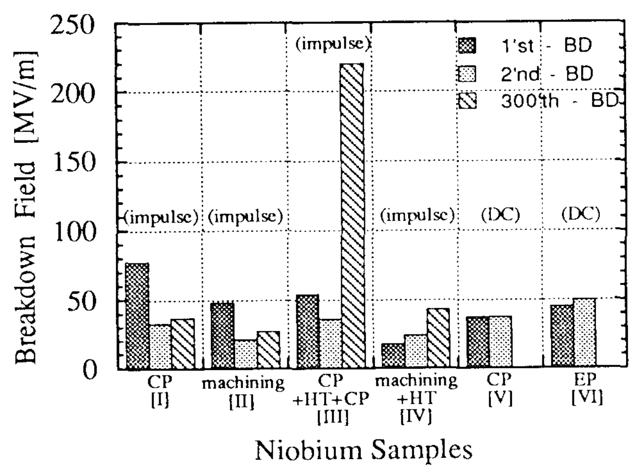

Fig. 5 Breakdown field of the niobium electrodes which were prepared by similar surface treatment to the niobium cavities.

Conclusion

An accelerating gradient of 30 MV/m, which exceeds the value required for TESLA, has been reproducibly achieved by the TRISTAN standard surface preparation. Field emission is not the major problem, and heat treatment at 1400°C is not indispensable to suppress field emission in this field region. The effectiveness of heat treatment at 1400°C, high pressure water rinsing and high purity niobium material will be investigated further.

References

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