SUPERCONDUCTING CAVITY BEAM TEST IN CESR*

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The first use of a superconducting accelerating structure in a storage ring is described.[1] Two 5-cell 1500 MHz "muffin tin" superconducting niobium cavities (1 m active length) were operated in the Cornell 8 GeV e^+e^- storage ring, CESR. A 6.1 mA beam was captured and stored at 3.5 GeV using only the superconducting cavity. Up to 12.5 kW was transferred to the beam by the cavity. Single bunch currents up to 12 mA were reached in conjunction with the normal 500 MHz RF. Beam induced higher order mode (HOM) powers of 290 W were carried to room-temperature loads by four couplers and waveguides; no HOM-induced cryogenic dissipation was detectable. Q's of the 76 most prominent resonances were measured. Transverse and longitudinal beam instabilities were studied by mechanically sweeping the tune of the cavities; current thresholds are compared to theory. The cavity exhibited the ability to survive breakdown at high incident power without degradation.

Introduction

The objective of this beam test was to demonstrate the feasibility of using superconducting cavities in a high energy e^+e^- storage ring. One of the most difficult problems associated with the use of superconducting cavities is the damping of beam-induced HOM's sufficiently that these modes do not cause longitudinal and transverse instabilities due to multi-turn effects. Although the number of 5-cell modules used in this test (two) is much less than the number involved in a higher energy machine[2] (typically 1000 modules at 20-50 GeV), the difference in radiation damping and bunch passage intervals is such that this test places more severe constraints on the HOM damping than does the higher energy machine. The results of this test can be translated using well established theory[3] to predict the performance of a higher energy machine.

Numerous other aspects of the use of superconducting cavities in the presence of a high peak current, short bunch-length machine were also investigated during this test, as described in the following.

System Description

Cavity, Peripheral RF Equipment, and Tuners

Many details of these items are described elsewhere.[4] The transmitter consists of a 60 kW CW klystron, a power splitter, and two circulators. Two cavity modules, with Nb waveguides attached, are shown in Fig. 1 as they appeared during assembly in the clean room.

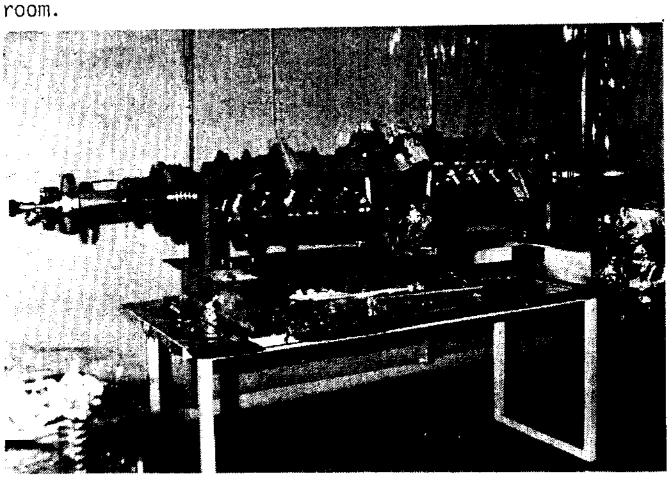

Figure 1

Cryostat, Cryogenics, and Cryogenic Controls

The cryostat consists of an aluminum liquid helium vessel, a Cu LN_2 shield with brazed-on LN_2 tubing, and an aluminum vacuum vessel. The two fundamental power waveguides and four HOM waveguides penetrate the cryostat radially.

Liquid helium is provided by a CTI-1430 refrigerator. LHe and sub-cooled LN_2 are transported to the cryostat by a 50 m transfer line. The LHe in the cryostat is cooled to 2.3°K by blower pumps. The bath temperature is accurately regulated by a motorized micrometer controlled throttle valve in the He gas pumping line. The He level in the cryostat is controlled by a JT valve.

RF Controls and Interlocks

Controls consist of an amplitude control loop (choice of incident power or field), a phase control loop, and tuning angle control loops (which control the mechanical tuners). Various interlocks interrupt the RF in case of poor vacuum, excess temperatures, or abnormal power conditions.

Accelerator Parameters

Some of the more important accelerator parameters, as they pertain to the use of superconducting cavities, are listed in Table I. Parameters listed for CESR are for the configuration in which the beam test was actually conducted. Parameters listed for CESR II are for a typical higher energy e^+e^- storage ring, optimized for the use of superconducting cavities.[2]

TABLE I

Symbol	CESR	CESR II	Units	Definition
E	3.5	50	GeV	Beam energy
U_o	0.19	1340	MeV	Synch. rad. loss per turn
U_{pk}	1.7	1500	MV	Peak RF voltage
f_{RF}	1.5	1.5	GHz	RF frequency
ν_s	0.065	0.14	-	Synchrotron tune
α	.0143	.00027	-	Momentum compaction factor
τ	46.6	0.68	msec	Radiation damping time
ℓ	1.0	500	m	Cavity length (active)
σ	1.1	0.34	cm	Bunch length (std. dev.)
N_b	1-2	4	-	Total number of bunches
q	30.8	33.6	nC	Charge per bunch
f_o	390	54.66	kHz	Bunch revolution frequency
C	768	5485	m	Ring circumference
h	3843	27444	-	Harmonic number
ν_H	9.39	~60.39	-	Horizontal betatron tune

The cavity, operating in CESR, is shown in Fig. 2.

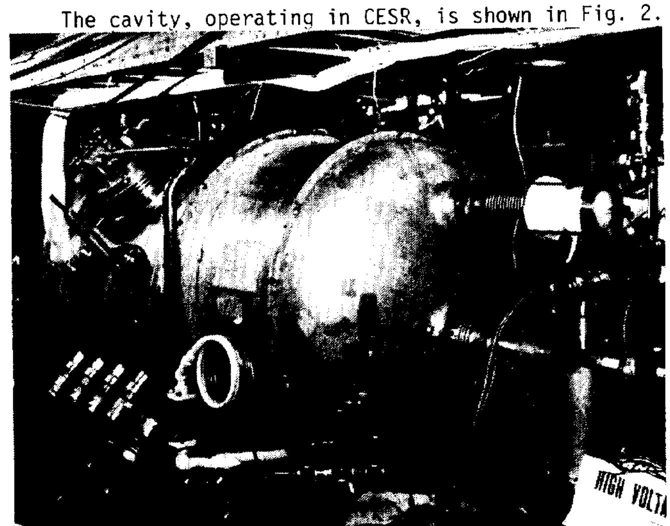

Figure 2

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Cavity Testing Procedure

Vertical Tests

The two cavities used in the beam test were tested on vertical test stands prior to installation in the horizontal cryostat. One cavity, which had anti-multipacting grooves only in the two cups with HOM irises, was limited by multipacting to E_{acc} = 2.16 MeV/m and $Q_0 = 5\cdot10^9$. The other cavity, which had anti-multipacting grooves in all cups, was limited by an inside crack left by a partial penetration beam weld between the HOM waveguides and HOM irises to E_{acc} = 1.9 MeV/m and $Q_0 = 3.2\cdot10^9$.

Following the beam test, two more fully-equipped 5-cell cavities were built which suffered from neither of these problems. Both exceeded our design objective of 3 MeV/m, and one exhibited $Q_0 = 3.2\cdot10^9$ and the other $Q_0 = 1.5\cdot10^9$.

Horizontal Tests

Following the vertical testing, the two cavities used were chemically processed and tested in the horizontal cryostat. The external waveguide was resonated so that the test could be performed with a 100 W amplifier rather than the klystron.

RF Tests in CESR

The cavities were then installed in CESR, and the above tests repeated. The first module exhibited E_{acc} = 1.8 MeV/m and $Q_0 = 1.7\cdot10^9$, and the second E_{acc} = 1.9 MeV/m and $Q_0 = 0.6\cdot10^9$. Both had field tilts of ±3%.

The static heat load of the cryostat without RF was 4.5 W at 2.3°K, plus 0.7 W at 4.2°K for the heat exchangers.

Beam Test

General

An electron beam was captured and stored using the superconducting cavity alone on April 18, 1982. The maximum current captured and stored using the superconducting cavity alone was 6.1 mA at 3.5 GeV, a limit imposed by the decrease in quantum lifetime as HOM losses increase with current.

The cavity voltage as determined by the probe calibration, the synchrotron oscillation frequency, and the quantum lifetime all agreed within ±3%.

The cavity was used in conjunction with the normal-conducting 500 MHz RF as both a bunch lengthener and shortener, yielding σ values between 1.1 and 5.2 cm, while the corresponding synchrotron oscillation frequencies varied from 34.75 to 7 kHz.

The highest single-bunch electron current reached was 12 mA.

No effect on either the cavity performance or the cryogenic load was observed by moving the beam around in the cavity, either horizontally or vertically.

Previous tests[5] of a superconducting cavity in the synchrotron established that superconducting cavities can tolerate $2\cdot10^{-9}$ Torr-years at each end of the cold region prior to warming up to release the gas, and that such cavities can tolerate more than 123 kRad of high energy radiation without degradation.

The present test also demonstrated that superconducting cavities, with suitable interlocks, can tolerate breakdown without degradation even though they are very heavily coupled to high power RF sources.

Fundamental Mode Measurements

Using normal and superconducting cavities at an energy of 5.14 GeV, the largest amount of power that could be transferred to the beam by the superconducting cavity was 12.5 kW at 7.8 mA.

HOM Power, Modes, and Impedances

Various machine impedance-related parameters were measured before and after the superconducting cavity was installed in CESR.

Coherent transverse damping rates and rates of change of longitudinal and transverse tunes and their harmonics with current indicate that wideband impedances are no problem at the currents of interest.[6,7]

Important higher order deflecting modes were identified by shaking the beam in the transverse direction at its betatron frequencies and by searching for large betatron sidebands on the HOM spectrum from one of the HOM couplers. Of the 25 strongest modes seen, the highest observed Q_L was 16600, and the average value 3800. Any value below 20000 is acceptable.

Calorimetric measurements at σ = 0.83 cm indicated a HOM power coefficient of 2.61 MW/A^2.

The extraction efficiency of HOM power was found to be at least 99.5%. This measurement was made by tuning the superconducting cavity off resonance and by measuring the 2.3°K dissipation with and without beam.

Of the ~15000 revolution harmonic lines seen, the highest frequency was at 12.6 GHz.

The resonance with the highest power observed was at 2.312 GHz, in excellent agreement with the bench measurements[8] which showed that a member of the TM_{111} passband at 2.31 GHz had the largest impedance of any of the higher order modes.

With a five-cell structure, the density of HOM's is relatively large. Some of these modes are damped much more heavily than others. The result of this is that the narrower resonances tend to be sitting on top of a rather flat background of unknown relative phase. In order to determine the Q's of these resonances, a least squares fit, including the background, was used.

Instabilities

As mentioned at the beginning of this paper, beam instabilities due to higher order modes are one of the principal concerns in the use of superconducting cavities in an e^+e^- storage ring, due to the very high Q's that these modes have unless externally damped. Using the cavity impedances measured on the bench, instability thresholds have been calculated using the same methods successfully used to predict the instability thresholds in several other machines.[3,7] The predictions of these calculations, for the accelerator conditions used in this experiment at 3.5 GeV and for the normalized impedances and external Q's measured on the bench for the superconducting cavity, are listed in Table II.

TABLE II

Effect	Probability	Threshold current, mA
Bunch lengthening	1	36
10% energy widening	1	28
Longit., 1 bunch, m=1	0.10	0.25
" " "	0.40	1.0
" " m=2	0.10	0.43
" " "	0.40	1.2
Trans., 1 bunch, ξ=.1	0.10	~20
" " "	0.40	~35
" 2 bunches "	0.10	1.9 (per bunch)
" " "	0.40	~12 (per bunch)

The effect of synchrobetatron resonances is one concern that has been expressed regarding the use of a frequency as high as 1500 MHz in a storage ring. The ratio of the width of such a resonance to the resonance spacing was smaller with the superconducting cavity than without it.

Detailed studies were made of the accelerating HOM resonances using a spectrum analyzer. Of the 76 modes measured, the Q_L in the worst case was approximately a factor of 4 below the allowed value; this factor was orders of magnitude lower in many cases.

The sum of the spectrum analyzer powers agreed with the power measured by calorimetry to within 19%.

In order to search for dangerous modes which could fall between the revolution harmonics and their sidebands, the mechanical tune of the cavity was varied over its available range. An attempt was made to hold the single bunch current between 2.5 and 4.5 mA. Instabilities caused by the upper fundamental f_s sideband are omitted. Microphonics could sometimes be used to identify the responsible resonance. The relative frequency of occurrence of various conditions are listed in Table III. The results of this table are consistent with the theoretical predictions (Table II) and indicate negligible probability of instability in a high energy ring at the currents of interest.

TABLE III

	Stable	Unstable, Spectrum Analyzer	Unstable, TV Image	Unstable With Loss	Row Total
No spectral lines implicated --------	0.28	0.14	0.03	0.07	0.52
Box modes implicated ----------------	----	0.01	0.06	0.12	0.19
Non-π, fundamental ------------------	----	0.12	----	0.03	0.15
π-mode, fundamental -----------------	----	0.07	----	----	0.07
Higher order modes ------------------	----	0.08	----	----	0.08
Column Total ------------------------	0.28	0.42	0.09	0.22	

During the beam test, the first coherent instability encountered under normal operating conditions at 3.5 GeV was an m = 1 longitudinal mode encountered with one bunch at 2.6 mA. This was cured by adding Robinson damping. The next instability was primarily an m = 2 longitudinal mode, but it also exhibited strong m = 1 sidebands. It was cured by longitudinal m = 1 feedback. Its threshold was 5.25 mA. Note that both of these thresholds are consistent with the theory.

The chromaticity was varied, with one and two bunches, to look for transverse instabilities. None was found.

Conclusion

We conclude from this beam test that the feasibility of using superconducting accelerating cavities in high energy electron storage rings has been demonstrated. Although certain technical difficulties were encountered in the test, the central objectives of the test were accomplished. The difficulties encountered are all capable of correction, and are not fundamental obstacles.

Use of a frequency as high as 1500 MHz in a storage ring presented no problems.

The utility of superconducting cavities in high energy storage rings has been further demonstrated by the successful test of the Karlsruhe "DORIS" cavity in PETRA at DESY on April 27, 1982[9] and by the excellent progress being made on storage ring cavities at CERN[10] and DESY[11].

Although the performance achieved in cavities fully equipped for storage ring service is quite adequate to make their usage worthwhile, further improvements in both field and Q would, of course, result in even greater economies. Further work also needs to be done to find the structure offering the optimum combination of performance and construction economy, and to engineer larger cryogenic modules which minimize costs associated with peripheral hardware, such as fundamental power feeds, higher order mode damping, and beam line transitions to room temperature.

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