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SUPERCONDUCTING RE-ENTRANT CAVITIES FOR HEAVY ION LINACS"

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Summary

Superconducting niobium cavities of reentrant shape have been built and tested at Stanford. The cavities have a 35cm diameter, 10cm length, and 2cm accelerating gap. They resonate at 430 MHz.

A large number of tests show that the performance of the cavities is reproducible: field strengths in excess of 12 MV/m were consistently achieved at Q values in the range 2 x 10^8 to greater than 10^{10} . The highest field obtained was 17 MV/m. To obtain these performance levels, our studies show that it is necessary to use special fabrication procedures, chemical treatment, and of perhaps greater importance, ultra high vacuum firing to temperatures of 1600 to 1800^9 C.

The geometry of the accelerating gap of the cavities in relation to the resonant frequency, make the cavities suitable for accelerating heavy ions with energies upward of 1 MeV/nucleon. A sequence of cavities could thus be used to boost the energy of particles obtained from existing tandem Van de Graaff accelerators.

Compared with a superconducting helix structure, the reentrant niobium cavities have a much greater mechanical stiffness, much larger surface area for cooling, comparable or better accelerating voltage gradients, and provide a single rather than a "double" accelerating gap per resonator. The latter feature makes it possible to build an accelerator as a sequence of independently controlled accelerating gaps. The phase and amplitude of each gap can be adjusted to provide essentially any velocity profile for the purpose of particle acceleration. Such an accelerator would be universal and could efficiently accelerate particles ranging from electrons through to uranium ions, provided the minimum injection energy of 1 MeV/nucleon is satisfied.

Introduction

Our group at Stanford, as well as others^{1,2,3,4} has been working on the development of superconducting resonators suitable for use in a linear accelerator. One application of such an accelerator would be to boost the energy of particles obtained from existing tandem Van de Graaff accelerators. Such a booster should have: a beam resolution and luminosity comparable to that achieved with present tandems; flexibility with respect to energy variation; the ability to accelerate different types of particles; simple injection and extraction features; and operating and capital cost in line with present day research budgets.

The key to meeting these requirements is the ability to control the phase and amplitude of each cavity independently. The low power dissipation per cavity (< 1 watt) makes this entirely economical and practical with present day electronic circuits.

Furthermore, the high mechanical stiffness that can be achieved with a reentrant niobium cavity makes it possible to maintain very small amplitude and phase fluctuations in the cavity field by using rf electronic feedback circuits and a piezoelectric transducers to control the cavity dimensions. $^{\circ}$ This enables beams with a small longitudinal phase space to be successfully accelerated. The limitation on the final energy resolution is then set by the intrinsic beam dynamics of a linear accelerator, rather than by some sort of practical difficulty. For instances, in a superconducting booster consisting of 90 cavities, the energy dispersion of the final accelerated beam would be $\Delta E/E \simeq 2~\times 10^{-3}$ for the case of injecting beam bursts with a phase length of 20°. Furthermore, it would be straightforward to debunch the beam at the output of the accelerator to reduce the dispersion to $\sim 5 \times 10^{-4}$ or less. To obtain a small phase length for the injected beam. the field levels and stability requirements on the chopper and buncher make it desirable to use superconducting cavities for these as well.



Fig. 1. Superconducting niobium cavity. The cavity is 35cm in diameter and resonates at 430 MHz.

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The simple shape of the reentrant cavity allows it to be manufactured in a straightforward way by hydroforming, machine tracing, and electron beam welding. Moreover, surfaces in the region of a high electric field can be optimally shaped to minimize field emmission and multipacting.

While the reentrant cavity has a some what lower shunt impedance than a spiral¹, split ring⁵, or helix, the high current-carrying surfaces of a reentrant cavity are much simpler to cool than the constrained surfaces of these inductively loaded structures. The reentrant cavity is of course unique in being a single gap accelerating structure.

Fabrication

Two full-sized niobium cavities were made and 25 tests conducted. Each test normally included some chemical surface treatment, UHV firing and extensive rf testing. The purpose of most of the tests was to determine the performance which could be expected from the cavities after the "standard" surface preparation and firing. A few of the tests were experiments with abbreviated surface preparation.

The electric field regions of the cavity were carefully designed to avoid any local field enhancement. As a result the field is quite uniform over the high field region. These cavities were produced by hydroforming two half shells of 0.2 inch niobium plate, followed by machining and mechanical polishing of the inside surfaces. Finally,electron beam welding was used to join the two halves. Various flanges, tubes, and struts were also welded onto the cavity to allow connection of the rf probe, connection of the furnace vacuum system, and to support the cavity during the high temperature UHV firing.

As the first step in most of the tests, the interior surfaces of the cavity were chemically cleaned. The cleaning usually consisted of only a light oxypolishing⁷, although several times a light chemical polish⁸ was used instead. In one case, Test 15, (see Table 1) cavity II was cut apart, then mechanically polished and electropolished⁹ before rewelding. A final anodization in NH₄OH always followed any chemical treatment.

Because superconducting cavities had been proven to be very easily contaminated by gases found in the air¹⁰ we felt that best results could be obtained if the cavities were fired with the rf probe, vacuum window, and valve already installed. This made it unnecessary to break the UHV of the cavity after firing to install these items which are needed for the rf testing. To accomplish this, after chemical treatment the cavity was attached to an axial rf probe unit and an all-metal valve as shown in Fig. 2. The cavity was then placed inside a special vacuum furnace actually consisting of two vacuum systems. One system pumped the bulk of the furnace and the exterior of the cavity using a Ti ball sublimation pump, and a 120 %/s Vac Ion pump. The second system, was connected to the valve on the cavity, pumped the interior of the cavity to UHV during firing using a 120 ℓ/s Vac Ion pump. A normal furnace treatment consisted of about 10 hours of firing at 1800 °C. After the firing, the HV system of the furnace bulk was opened, exposing the outside of the cavity and the valve. In this position the valve could be closed and the cavity and valve disconnected from the UHV pump without exposing the cavity's interior to air.

The rf tests were made in a 14 inch vertical research dewar at temperature near 2° K. Precise temperature regulation was not attempted. An external oscillator was locked to the cavity frequency by a reflectometer. A pin diode switch and amplifier chain provided up to 15 watts of rf power which could be pulsed. Rf power was coupled axially through a single electric probe (shown in Fig. 2) which had been permanently adjusted to give a coupling Q near 0.3 x 10° . The coupling was set at this value to allow reasonable amounts of power to be coupled into the cavity to overcome multipacting levels and to allow helium ion processing. This coupling allowed measurement of Q_0 values up to, but not exceeding 10^{10} .

During the measurements, values of Q_0 , peak surface electric fields, and radiation emitted by the cavity were measured. The decay method was used to measure Q_0 values to an accuracy of $\pm 5\%$ in the range of 10^9 to 10^9 . Above $Q_0 = 10^9$ measurements were increasingly inaccurate due to the over-coupling of the probe. The upper limit that could be measured for Q_0 was 10^{10} . The peak surface field was determined by measuring the rf energy stored in the cavity and using the ratio K = E_p/U_2 = 18 MV/m. J_2 to convert this to a peak electric field value. This value of K was taken from a computer calculation of the fields in our particlar cavities and is estimated to be accurate to $\pm 7\%$.

In more recent tests, helium ion processing¹¹ was used to reduce electron loading in the cavity. For this purpose, the cavity and valve assembly was placed in the research dewar for rf testing and connected to a special helium ion processing pumping system. This system consisted of a variable leak connected to a helium supply to admit helium, and a turbo-molecular pump to subsequently remove the helium. A remote drive was installed on the cavity valve to allow it to be opened after cool down, and initial measurement. This allowed comparison of results before and after helium ion processing. It also delayed exposing the cavity's interior to the vacuum of the helium ion processing system until after the connecting tubing was cold and could serve as a cold trap to prevent possible contamination from reaching the cavity.



Fig. 2. Full scale niobium test cavity complete with rf probe unit and vacuum valve ready for UHV firing.

The helium ion processing was carried out at a pressure of 10^{-4} to 10^{-5} torr of helium with the cavity operating at fields just slightly less than break-down.

Test Results

A total of 25 tests have been made on two cavities. In several instances definitive results were not obtained because of failures or problems associated with either the hardware used for the cavity processing or testing. However, many tests proceeded as planned. A summary of seven such successful tests is given in Table 1.

Test no. 10 of cavity I was typical of a successful test. A Q_0 versus peak surface electric field (E_p) plot of this test is shown in Fig. 3. As shown, Q_0 is greater than 10^{10} over the whole range of fields except for a slight dip in the normally seen multipactoring level at 1 to 3 MV/m and except for the final abrupt drop in Q_0 just before 16 MV/m where the cavity experienced breakdown. This drop in Q_0 was accompanied by increasing amounts of radiation, up to 30 mr/hr, measured outside the dewar. It was obviously the result of some type of electron loading which finally initiated breakdown at 16 MV/m. The magnetic field at breakdown was only 24 mT.

The results with cavity II were less impressive. Almost all the tests on this cavity were plagued with probe or vacuum failures. In the single test which was some what successful, the cavity had not been given the necessary chemical treatment. Still, this test yielded the very high Q_0 's of test 10. However, these fell abruptly to a breakdown near 10 MV/m. This some what disappointing field performance of cavity II could be due to a lack of chemical treatment or to niobium ball found spattered on the inside of the cavity when it was cut apart after test 15.



Fig. 3. Test results of cavity I for test 10. A Q_0 greater than 10^{10} could not be measured due to over coupling of the fixed rf probe. Breakdown occured at 16 MV/m.

The balls were apparently spattered on the interior surface of the cavity when the two halves were welded together. It is now believed that the mating surfaces of the halves were not correctly machined prior to welding.

After cavity II was cut apart, the two halves were mechanically repolished and then electropolished. Care was taken to insure that the mating surfaces were correctly machined prior to welding the two halves together. This cavity has been subsequently relabelled as cavity IIA. In tests 23, 24, and 25 on cavity IIA, fields of 10, 10.5, and 12.5 MV/m were obtained. Although this represented an improvement over cavity II, the fields were still below that of cavity I.

Helium ion processing was tried in tests 24 and 25 and succeeded in raising the fields to a more respectable 12.5 and 17.3 MV/m. The initial results with helium ion processing were very encouraging when properly carried out so that air or other residual gases in the vacuum system did not accidentally contaminate the cavity. Moreover, the helium ion processing did not reduce the cavity Q_0 value. On the contrary, the Q_0 value increased and raised the point at which breakdown occured. More experiments are under way to confirm these initial results and also apply helium ion processing to cavity I.

A number of tests were conducted to determine what was required to restore the good performance of a cavity that had been contaminated by poor vacuum conditions. Three such tests were tried. In each test the cavity was exposed to air and without any chemical treatment it was UHV fired in situ at temperatures of 400, 1000, and 1800° C in Tests 17, 18, and 19 respectively. The results were disappointing. In the two lower temperature tests, the cavity's initially low Q degraded to below 10° upon application of much power at all. Attainment of respectable fields was not possible. In test 19 after a 1800° C firing, the some what more respectable Q₀ of 6 x 10° and a field of 6 MV/m were reached. However, it was not until Test 21, when the cavity had been chemically treated then fired at 1800° C, that the full potential

TABLE 1. SUMMARY OF CAVITY TEST RESULTS

Test No.	Processing*	Firing Temp.(°C)	Low Power Q _o (G)	^E p (MV/m)
Cavity I				
10 16 21	C, A None O, A	1600 1800 1700	>10 >10 >10	16 15 17
Cavity II				
15	None	1750	10	9
Cavity IIA				
23 24	M,E,O,A Vacuum degrad HIP	1800 ed	>10 10 1.5 10.5 1.8 12.5	
25	O,A HIP	1800	8 10	12.5

°C - chemically polished, O - oxypolished,

A - anodized, M - mechanically polished, E - electropolished, HIP - helium ion processing. of this cavity was reclaimed. In that last test, a Q of greater the 10^{10} and a field of 17 MV/m were reached.

Conclusions

Our test results have shown that very attractive electric fields and Q_0 can be consistantly obtained if the cavities are given the proper chemical surface treatment and furnace firing, and if UHV conditions are carefully maintained. In the event of vacuum failure, the tests indicate that good performance can be restored by additional oxypolishing, anodization, and vacuum firing.

Further tests are underway to determine what, if anything, is presently limiting cavity fields to 17 MV/m. It is hoped that application of helium ion processing to cavity I will yield still higher fields.

On the other hand, the already achieved fields greater than 12 MV/m at high Q_0 values, indicate that the use of these cavities in a superconducting booster, is quite attractive and could result in average heavy ion acceleration gradients greater than 1 MV/m.

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