Performance of Superconducting Cavities for CEBAF

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Abstract

The Continuous Electron Beam Accelerator Facility (CEBAF) is presently under construction in Newport News, Virginia. The accelerator consists of ~160 meters of 5-cell niobium cavities manufactured from high thermal conductivity niobium with RRR values > 250.

After an initial six month period of first article manufacturing at a rate of 3 cavities per month, the full production rate of 12 cavities per month was reached in October 1990. These cavities are chemically treated at CEBAF, assembled into hermetically sealed cavity pairs and tested in a vertical configuration prior to installation into the accelerator.

The performance of all cavities received from the manufacturer and tested at CEBAF has exceeded CEBAF's design criteria for Q value $> 2.4 \times 10^9$ at 2 K and an accelerating gradient $E_{acc} > 5$ MV/m. Q_0 values as high as 10^{10} and accelerating gradients of $E_{acc} \geq 18$ MV/m have been achieved.

INTRODUCTION

CEBAF will provide a low emittance electron beam with a current of 200 μA and electron energies up to 4 GeV for fundamental experimental studies in nuclear physics.[1]

It comprises two anti-parallel linear accelerators arranged as a racetrack. They each consist of 160 superconducting niobium cavities of a total accelerating length of approximately 160 meters; 18 additional cavities of the same type are used in the injector. These cavities are assembled into hermetically sealed pairs[2], which in turn are installed in a single helium vessel forming a cryounit. Four such cryounits are joined into a cryomodule with a common insulation vacuum; the cryomodule represents the smallest unit that can be independently cooled and installed or removed from the accelerator system.

The 5-cell cavities with an elliptical cross section and an active length of 0.5 meters are kept at 2 K by means of a 5 kW refrigerator, which is located in the center of the racetrack accelerator. The cavities are excited in the accelerating mode at 1497.000 MHz and are operated at an accelerating gradient of at least 5 MV/m. At this gradient, each cavity will dissipate not more than 5.5 watts of RF power.

In order to achieve these low losses in the cavity walls and the high accelerating gradients, particular care has to be taken during the manufacturing processes for material and cavities and for the chemical processing and assembly of the cavities.

This paper describes CEBAF's approach for meeting the stringent requirements for quality of material and cavity manufacturing and discusses available results on cavity performance.

MATERIAL REQUIREMENTS AND CAVITY FABRICATION

For a long time, superconducting niobium cavities have been limited in their performance by thermal instabilities in the cavity walls. As an important result of investigations into the causes of these instabilities, it was found that they occur at local material defects and are stabilized by improved thermal conductivity of the cavity material.

High thermal conductivity niobium, with λ > 60 W/mK, has been chosen as the cavity material for areas of high electromagnetic fields in a cavity to sustain thermal instabilities [3].

For parts of the cavities which have to sustain only moderate RF fields, reactor grade niobium with a thermal conductivity of ~8 - 10 W/mK is being used.

Other important parameters for the material include requirements for grain size, which influences the deep drawing capability of cavity parts, and for the tensile properties. Simulation calculations using stress analysis codes on the real cavity shape under realistic load conditions resulted in a requirement of a yield strength greater than 13500 psi for the waveguide parts of the cavity and > 10700 psi for the cavity cells[4].

Table 1 summarizes CEBAF's material requirements as specified for reactor grade and RRR grade niobium.

For the accelerator system, CEBAF adopted the Cornell design of a cylindrical symmetric 1500 MHz cavity with elliptical cross section, which had successfully been used for storage ring application[5].

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Table 1

Niobium	Cavity Part	RRR	Grain Size	Yield Strength	Elongation
Reactor	Couplers Flanges	~40	ASTM>6	>13500 psi	>25%
RRR	Cells	>240	ASTM>6	>10700 psi	>25%

The main features of this cavity are: shunt impedance 959 Ω/m, $E_{surf}/E_{acc}=2.56$, $H_{surf}/E_{acc}=4.68$ mT/MV/m, G=276 Ohm. Two of these cavities are assembled into a hermetically sealed pair. This is accomplished by adding a ceramic RF window[6] to the fundamental coupler flange, closing off the HOM waveguides with HOM loads[7] and adding gate valve assemblies at the beam pipe end of the cavity. In this concept, the inner cavity surfaces, which carry the RF current, are kept under vacuum at all times after the initial assembly and the risk of contamination due to exposure to air during assembly operations is minimized.

CEBAF awarded a manufacturing contract for the 338 cavities needed for the accelerator to Interatom after a competitive bidding process involving 5 qualified manufacturing companies. In addition, several cavities have been built "in-house" by a job shop approach.

The essential manufacturing steps (see details in Ref. [8], this conference) are specified in CEBAF's "Statement of Work" and following the manufacturing drawings and processes developed at LNS of Cornell University, are:

A) Deep drawing and machining of cavity components without deterioration in the quality of the material.

B) QA of the manufactured parts and removal of any kind of visual surface irregularities like scratches, dent, voids, inclusions.

C) Final chemical cleaning of manufactured parts prior to electron beam welding.

D) Electron beam welding of the parts with full penetration welds, smooth weld appearance, free of weld splatter and voids, in a vacuum of $< 5 \times 10^{-5}$ Torr.

E) Leak checking of the finished cavity, tuning of the cavity to obtain the specified frequency and field profile flatness in the accelerating mode and final machining of the cavity to achieve the specified mechanical tolerances.

Strict adherence to these procedures coupled with good workmanship is a stringent requirement to meet CEBAF's design specification of $Q > 2.4 \times 10^9$ at 2K and 5 MV/m.

CAVITY ASSEMBLY AND TESTING

The performance of each cavity is tested prior to assembly into the accelerator. After a series of QA checks, the cavities are chemically polished in a buffered chemical solution of nitric, hydrofluoric, and phosphoric acids, resulting in a removal of ~60 μm. Thorough rinsing in ultrapure water, ultrasonic agitation, twofold rinsing with reagent grade methanol follows prior to the assembly of 2 cavities into a hermetically sealed pair inside a Class 100 cleanroom (Fig. 1).

After establishing a vacuum of $< 10^{-6}$ Torr in the hermetically sealed units, they are attached to a cryogenic test system and cooled down to helium temperature in a vertical configuration. During this cooldown from room temperature to 4.2 K, which typically is accomplished in 2 hours and reduces the danger of Q degradation due to Nb-H precipitation[9], the external magnetic field, which is present at the cryostat, is shielded to < 10 mG (details in Ref. [10], this conference). Variable coaxial to waveguide input couplers are part of the test system. They permit the excitation of each individual cavity at minimum reflected power.

The RF testing is done with a conventional manual RF system, which utilizes a VCO/amplifier circuit being phase locked to the cavity.

TEST RESULTS AND DISCUSSION

A typical performance characteristic of a cavity pair is shown in Fig. 2 where the Q_o value is plotted vs the accelerating gradient.

To date, CEBAF has received 76 cavities from Interatom and 52 tests have been conducted on these cavities assembled to pairs. In addition, 16 cavities have been built "in-house" and 8 of these have been tested. The experience with these cavities/pairs can be summarized as follows.

A) All cavities exceeded CEBAF's design criteria of a Q value $> 2.4 \times 10^9$ at 2 K and a gradient of $E_{acc} = 5$ MV/m, in the <u>first</u> test except for 3 cavities. These failures in the early stages of the program were due to insufficient material removal.

B) The average gradient of all above specification tests carried out on Interatom cavities is presently 10 MV/m, a factor of 2 above the design gradient.

In several tests, gradients > 15 MV/m have been measured and the highest gradient obtained in one cavity of a pair was 18 MV/m. The gradients were always limited by excessive field emission loading.

C) The reciprocally averaged Q_o value at 2 K and 5 MV/m is 7.6×10^9, a factor of 3 higher than the design value.

D) A significant number of cavity pairs had to be reworked because of peripheral problems such as leaks or mechanical problems with the test setup. Leaks caused by external hardware have been identified and corrected, leaks at indium joints are presently being reduced by improving the surface conditions and mechanical rigidity of the sealing surfaces.

E) The statistics of all cavity pair results are summarized in Fig. 3, where the maximum gradient is plotted vs the Q_o value at 5 MV/m.

CONCLUSION

CEBAF has successfully assembled and tested several cavity pairs with performance exceeding CEBAF's design criteria by a good margin.

Q values in excess of 10^{10} and gradients as high as 18 MV/m have been achieved. This proves that the methods used for cavity fabrication and processing are working and that superconducting RF has matured to a reliable technology.

Unanticipated mechanical problems with leaks in auxiliary systems point to the necessity of very stringent QA measures. The combination of superconductivity, vacuum and cryogenics at 2 K poses an extraordinary challenge to the successful implementation of a large scale system.

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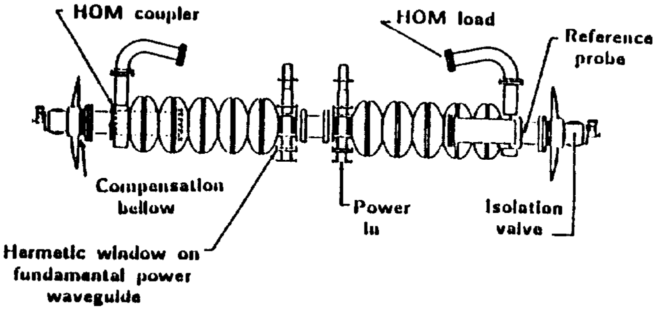

Fig 1.: Cavity Pair

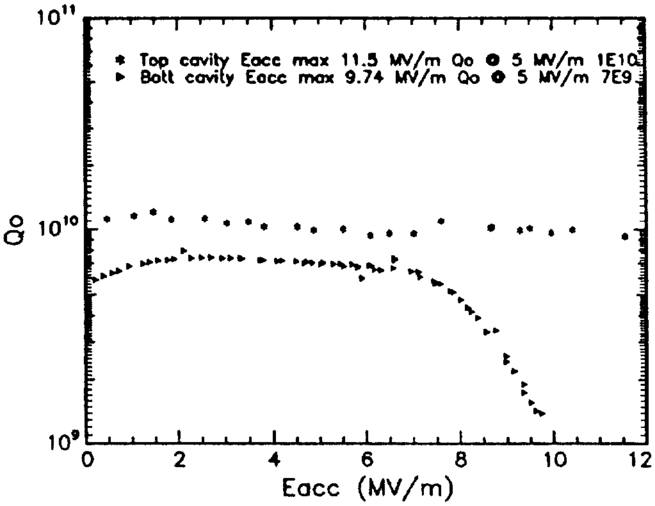

Fig. 2: Typical Q_o vs E_{acc} for a Cavity Pair

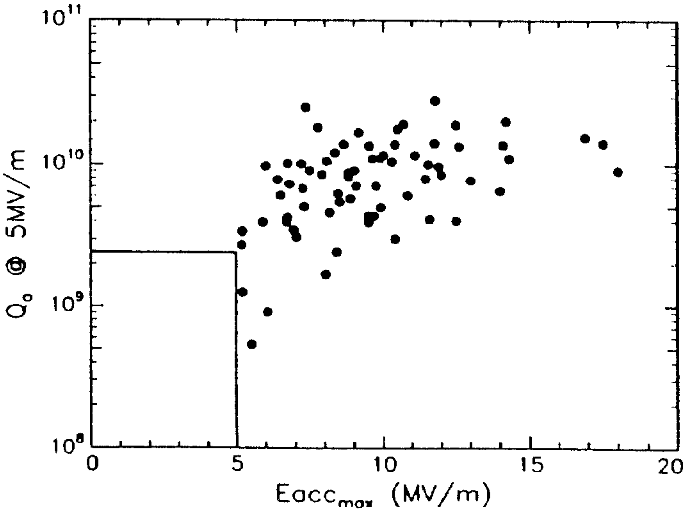

Fig. 3: Summary of Test Results on Cavity Pairs