FINE GRAIN AND LARGE GRAIN NIOBIUM CAVITY PROTOTYPING FOR A PROTON LINAC*

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Abstract

A superconducting cavity has been designed and prototyped for acceleration of particles travelling at 81% the speed of light ($\beta = 0.81$). The application of interest is an 8 GeV proton linac proposed as an upgrade to the Fermilab accelerator complex, although the cavity would also be suitable for other ion accelerators. The cell shape is similar to that of the 805 MHz high-beta cavity developed for the Spallation Neutron Source Linac, but the resonant frequency is 1.3 GHz and the beam tube diameter matches that of the 1.3 GHz cavity for the TeSLA Test Facility. Four single-cell prototypes have been fabricated and tested before and after post-purification. Two of the cavities were formed from standard high purity fine grain niobium sheet; the other two were fabricated from large grain niobium, following up on the work at Jefferson Lab to investigate the potential of large grain material for cost savings and/or improved RF performance. Two 7-cell cavity prototypes (one fine grain, one large grain) have also been fabricated. The single-cell results are presented in this paper, and the status of the prototyping effort is reported.

INTRODUCTION

Six-cell elliptical cavities for $\beta = 0.61$ and $\beta = 0.81$ are now being used for acceleration of protons in the Spallation Neutron Source (SNS) linac at Oak Ridge [1]. A seven-cell superconducting cavity similar to the $\beta = 0.81$ cavity for the SNS linac has been designed. Possible applications include a proposed 8 GeV proton linac at Fermi National Accelerator Laboratory (FNAL) [2, 3]. The proposed linac at FNAL would employ 1.3 GHz $\beta = 1$ cavities developed for the TeSLA Test Facility (TTF) [4] at the high energy end. The FNAL $\beta = 0.81$ cavity was designed to have the same frequency (1.3 GHz instead of the SNS frequency of 805 MHz) and beam tube diameter (in between the unequal left and right beam tube diameters of a scaled SNS $\beta = 0.81$ cavity) as the TTF cavity.

Following up on the work at Jefferson Lab to investigate the potential of large grain material for cost savings and/or improved RF performance [5], two of the $\beta = 0.81$ single-cell prototype cavities were fabricated from large grain niobium (the half-cells were made from disks with < 10 grains). The other two cavities were made from the traditional fine grain niobium (grain size of ~ 60 μm). Two 7-cell cavities have been fabricated, one from the fine grain material, and the other from the large grain material. The single-cell cavities have all been tested several times, with thermal treatments between tests. The 7-cell cavities have not yet been tested.

This paper reports on the $\beta = 0.81$ prototyping effort. First results on the single-cell prototype cavities were reported previously [6, 7]. In the mean time, post-purification and additional testing was done on the fine grain single-cell cavities, allowing for a direct comparison of fine grain and large grain cavity performance.

CAVITY DESIGN

RF calculation for the FNAL cavity were done with SUPERFISH [8]. The electric field lines for the 7-cell can be found in a previous paper [6]. Selected cavity parameters for the 7-cell and single-cell FNAL cavity are given in Table 1. The corresponding values for the TTF [4] and SNS [9] cavities are also included for comparison. The wall inclination of the FNAL cavity is the same as for the SNS cavity, but the cell-to-cell coupling is slightly higher, al-

Table 1. Selected parameters for the $\beta = 0.81$ FNAL cavity and comparison with SNS and TTF cavities; E_a = accelerating gradient, E_p = peak surface field, B_p = peak surface magnetic field, c = speed of light, R = shunt impedance (linac definition), and Q = quality factor.

Cavity	TTF 9-cell	SNS 6-cell	FNAL 7-cell	FNAL 1-cell
geometrical β	1	0.81	0.81	0.81
wall inclination	13.3°	7°	7°	7°
E_p/E_a	2.0	2.19	2.19	2.18
cB_p/E_a	1.28	1.44	1.41	1.58
cell-to-cell coupling	1.8%	1.5%	1.6%	-
R/Q per cell	115 Ω	80.8 Ω	79.1 Ω	62.3 Ω
Geometry factor	270 Ω	233 Ω	227 Ω	229 Ω

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lowing for 7 cells instead of 6. The RF parameters of the FNAL and SNS cavities are similar. More information on the cavity design is available in a separate report [10].

CAVITY FABRICATION AND PREPARATION

Sheet Nb of thickness 2.8 mm was used. Forming of the half-cells and beam tubes was done at MSU and in the local area; electron beam welding was done by industry. Nb-Ti flanges with knife edges were electron beam welded to the beam tubes. Partially welded cavities are shown in Figure 1. The grain boundaries of the large grain half-cell (Figure 1b) are clearly visible. Some of the fabrication steps were modified for the large grain cavities due to the unique characteristics of the material. The procedures and observations associated with the fabrication of the large grain cavities are discussed in a separate paper [7].

The preparation steps prior to RF testing were acid etching with a Buffered Chemical Polishing (BCP) solution and high-pressure rinsing with ultra-pure water in a clean room. The inside surface of the cavity was etched, but the outside surface was not.

Some of the cavities underwent a low-temperature bake-out, with RF testing done before and after the bake-out. The bake-out was done for about 12 hours at a temperature of 120°C, with vacuum inside the cavity.

After RF testing, all cavities underwent titanium treatment to remove oxygen impurities. The cavities were fired in a vacuum furnace for 3 hours at 1250 °C, with a Ti box around the cavity.[1]

Figure 1. Fine grain (top) and large grain (bottom) half-cells after the iris weld.

Fine Grain Cavities

Rolled Nb sheet of RRR $\geq$ 260 was used for the fabrication of the fine grain cavities. Cu gaskets were used with the knife edge seal on the Nb-Ti flanges for the RF tests. Neither the half-cells nor the completed cavities were fired in a vacuum furnace prior to the first RF tests. The cavities were etched with BCP solution (chilled 1:1:2 mixture) to remove about 180 μm after fabrication; 30 to 50 μm was removed in the case of repeat etching. The cavities were high-pressure rinsed for 45 to 120 minutes. The first cavity was tested 4 times, with several additional cycles of etching and rinsing. The second cavity was tested twice, with a vacuum bake-out after the first RF test.

After the initial rounds of RF testing, both cavities underwent Ti treatment. They were then etched (to remove another 40 μm), high-pressure rinsed for 60 minutes, and RF tested again. Additional RF testing was done after removing another 10 μm and repeating the high-pressure rinse.

Large Grain Cavities

For the fabrication of the large grain cavities, Nb sheet was cut via wire electric discharge machining (EDM) from an ingot with RRR $\sim$ 280 and Ta content $\sim$ 800 ppm. After the iris weld, the half-cells were mechanically polished to smooth off grain boundaries. Prior to the first RF test, the cavities were fired in vacuum at 600°C for 10 hours to eliminate hydrogen from the material. A 50 μm etch (BCP, unchilled 1:1:1 mixture) was done before firing, and another 50 μm etch was done after firing. Because of issues that arose during the etch, the knife edges were machined off and indium seals were used instead. The cavities were high-pressure rinsed for 60 minutes.

After etching and rinsing, both cavities were RF tested; they were tested a second time after a vacuum bake-out. The cavities then underwent Ti treatment, followed by etching to remove 50 μm and high-pressure rinsing. They were then RF tested before and after an additional vacuum bake-out.

RF TESTING

The fine grain cavities were tested at MSU prior to Ti treatment; they were tested at Jefferson Lab after Ti treatment. The large grain cavities were tested at Jefferson Lab. Figure 2 shows one of the fine grain cavities on the RF test stand.

[1] Note that the firing time was erroneously reported as 2 hours in previous papers [6, 7].

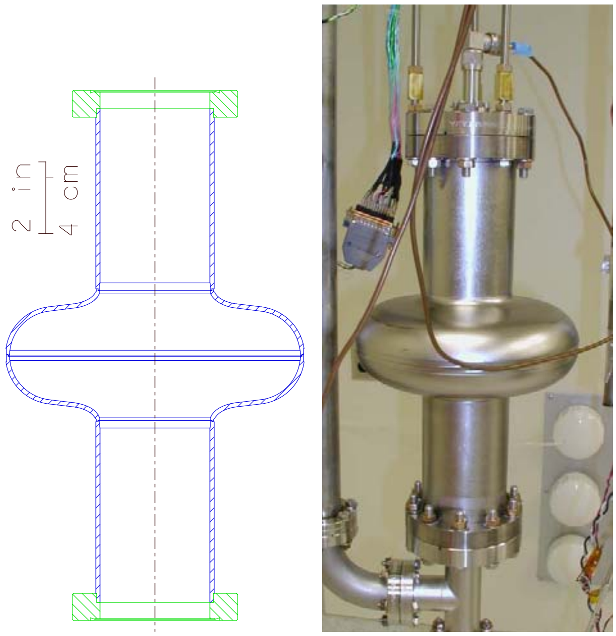

Figure 2. Left: Drawing of single-cell $\beta = 0.81$ cavity. Right: Fine grain cavity on insert for RF test.

Tests Prior to Ti Treatment

The RF tests before Ti treatment were reported previously [6, 7]. The highest gradient reached in the fine grain cavities without Ti treatment was $E_a = 18$ MV/m, corresponding to $E_p = 40$ MV/m and $B_p = 96$ mT; both fine grain cavities were ultimately limited by hard barriers ("quench").

Both large grain cavities were tested before and after vacuum bake-outs. High field Q-drop was observed in the initial tests; higher fields could be achieved after baking. The highest gradient reached in the large grain cavities prior to Ti treatment was $E_a = 27$ MV/m, corresponding to $E_p = 58$ MV/m and $B_p = 139$ mT.

Thus, before Ti treatment, significantly higher fields were achieved in the large grain cavities relative to the fine grain cavities. However, as indicated above, the large grain cavities had been fired at 600°C, while the fine grain cavities had not been fired.

Tests After Ti Treatment

After Ti treatment, the fine grain cavities reached significantly higher fields. The performance of the large grain cavities did not change very much. RF measurements on all four cavities after Ti treatment are compared in Figure 3a. The RF performances of the fine grain and large grain cavities are similar.

The large grain cavities underwent a vacuum bake-out and were retested. As can be seen in Figure 3b, the bake-out alleviated the high-field Q slope, and allowed both cavities to reach higher fields. Both cavities were limited by quenches. The highest field reached was $E_a = 28$ MV/m, corresponding to $E_p = 62$ MV/m and $B_p = 148$ mT.

Note that the results presented here for the large grain cavities are the same as reported in the previous paper [6]; the results for the fine grain cavities after Ti treatment are reported here for the first time.

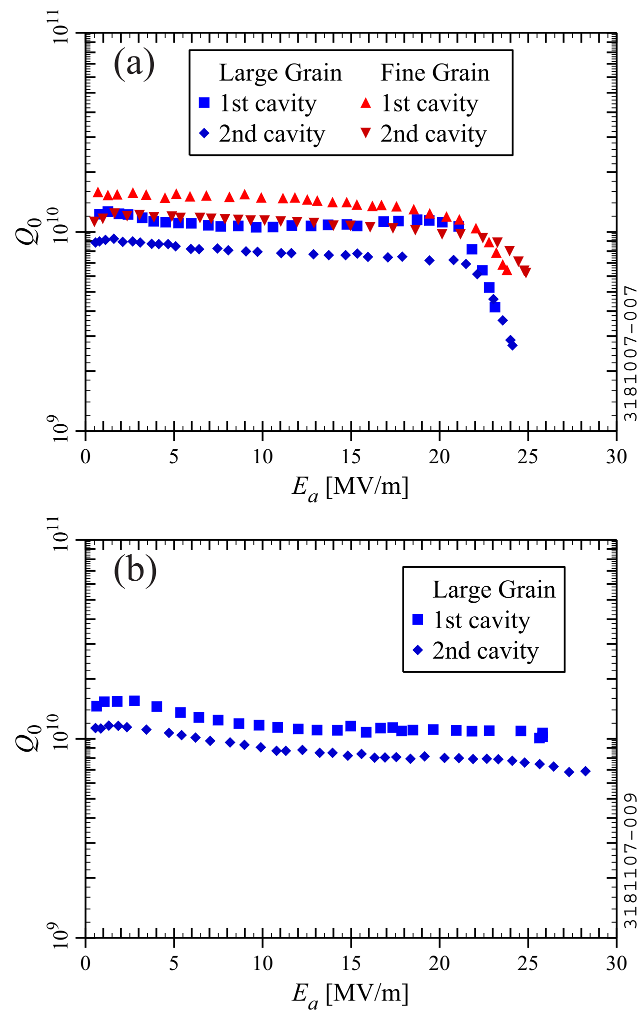

Figure 3. RF test results at 2 K for (a) all cavities after Ti treatment and (b) large grain cavities after an additional vacuum bake-out.

Residual Resistance Measurements

The residual surface resistance was inferred from several measurements of the low-field Q_0 as a function of temperature, both before and after Ti treatment. Measured residual surface resistance values for the large grain cavities were between 8 and 14 nΩ. Measured values for the fine grain cavities were similar: between 6 and 13 nΩ. No clear correlations were observed between Ti treatment, baking, and the measured residual resistance.

SEVEN-CELL CAVITY FABRICATION

The starting material and procedures for fabrication of the 7-cell cavities were the same as for the single cell cavities. One exception was that the single-cell equator welds were all full penetration welds done from the outside, but some of the equator welds for the 7-cell cavities were done from the inside.

Figure 4 shows a drawing of the 7-cell cavity, along with photographs of the completed cavities. Figure 5 shows a close-up photograph of the large grain 7-cell cavity.

CONCLUSION

Reasonable RF performance, adequate for use in a proton linac, was reached in all 4 single-cell 1.3 GHz $\beta = 1$ prototype cavities. After post-purification, similar gradients were reached in all 4 cavities, independent of grain size. Additional low-temperature baking was done on the large grain cavities, producing some further improvement in the high-field performance. Two 7-cell cavities have been fabricated, one from fine grain Nb and the other from large grain Nb. Field flatness tuning and cryogenic testing of the 7-cell cavities has not yet been done.

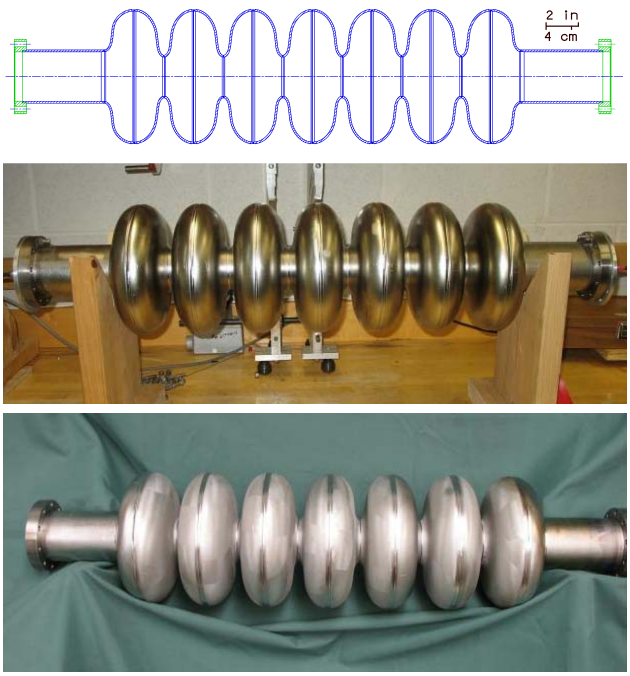

Figure 4. Top to bottom: drawing of 7-cell $\beta = 0.81$ FNAL cavity (blue = Nb; green = Nb-Ti); photographs of the completed fine grain cavity and large grain cavity.

Figure 5. Close-up photograph of the large grain 7-cell cavity.

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