HIGH FIELD TEST RESULTS OF SUPERCONDUCTING 3.9-GHZ ACCELERATING CAVITIES AT FNAL

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Abstract

The XFEL facilities are planning to use a section with several third harmonic cavities (3.9 GHz) to improve beam performance [1]. Fermilab is developing the superconducting third harmonic section for the FLASH (TTF/DESY) upgrade. This section will include four cavities equiped with couplers and blade tuners installed in a cryostat. Currently, two cavities are completed and one of them is under vertical test. The gradient of this cavity was limited by multipacting in the HOM coupler. Visual inspection of the HOM couplers after cold tests showed that both couplers were damaged. In this paper we discuss the results of the vertical tests, an analysis of multipactoring in the HOM coupler, and a new design for the HOM coupler.

INTRODUCTION

The 3rd harmonic 3.9 GHz cavity was proposed to linearize energy distribution along the bunch before the bunch compressor. These cavities operate in the TM010 mode and will be located downstream of the 1.3 GHz TESLA type cavities. The required operating gradient is 14 MV/m. Fermilab has agreed to provide DESY with a cryomodule containing a string of four of these cavities. In addition, a second cryomodule with one cavity will be fabricated for installation in the Fermilab photo-injector, which will be upgraded for the ILC accelerator test facility. In the scope of this project Fermilab is developing cavities, couplers, blade tuners and a cryostat [2-5]. The construction and successful test of key components (copper and niobium cavity prototypes, helium vessels and blade tuners) allowed us to start cavity production after several minor modifications in design. Current status of the production and the first results were presented in [3,4]. The overall objective is to build eight 3rd harmonic cavities. The first cavity, a prototype design, was completed in December 2005.

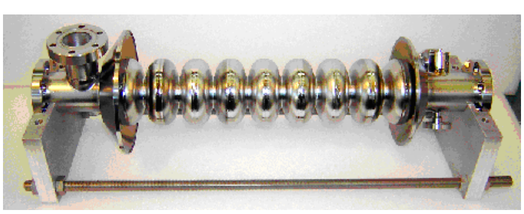

Figure 1: Cavity No. 2 before etching.

Lessons learned suggested several minor design changes that were incorporated into the remaining seven cavities. Fabrication of the cavities is a collaborative effort. Fermilab will build four cavities (including the prototype), and JLAB will build the remaining four cavities (using parts supplied by Fermilab). Cavity No. 2 was completed at Fermilab in Jan, 2006 (Fig. 1). It is currently under test.

COLD TEST RESULTS

Test of the 3-Cell Cavity

The first niobium 3-cell prototype was built to test cavity performances and develop tooling and technology. There are no HOM or main couplers on this cavity. The results of the cold tests were reported in [3-5].

Initially the cavity was etched ~140 μm inside (measured by etching rate, not frequency) and 20 μm outside and then treated for 10 hrs at 600º C. The first test showed a field emission problem, which was fixed after appropriate high pressure rinsing. The best achieved residual surface resistance was 6 nΩ (measured at 1.4° K). A typical resistance of ~50nΩ at 1.8° K corresponds to a Q_0 of ~6.e+9. The cavity was quenched at an accelerating gradient of ~19 MV/m (surface peak magnetic field of ~105 mT) and this threshold can be explained by a thermal breakdown model [6]. This surface field corresponds to an accelerating gradient of ~21 MV/m in a 9-cell cavity, which is well above the design gradient of 14 MV/m. We are planning to use this cavity as a reference cavity to check performances of the buffered chemical polishing (BCP) and high pressure water rinsing (HPWR) facilities.

Test Results of the 9-Cell Cavity

The first 9-cell Nb cavity (prototype) failed during the deep BCP. After a ~130 μm etch a hole developed in one of the HOM couplers, which has thinner wall thickness than in the final design. Cavity No. 2 was successfully manufactured, tuned, and tested after BCP, high temperature treatment (10 hrs at 600° C) and HPWR.

Initial measurements showed a very high residual resistance Rres=3000 nΩ. After operating with high fields in the "π" and "0" modes, the residual resistance dropped off to ~80 nΩ. Processing was done at a pulsed power of 120 W and a duty factor varying from 1% to CW. Additional high field processing for two more days improved residual resistance to 40 nΩ.

The history of Q vs E measurements is shown in Figure 2. In the cavity tests we observed strong multipactoring, which causes Q-slope at small field levels. After high field "processing" the Q improved for small fields and the multipacting level shifted from ~0.5 MV/m accelerating gradient to ~2.5 MV/m. In the last CW test, with higher resonant frequency of the HOM coupler (see below), the achieved gradient was 4 MV/m. In the pulsed regime the accelerating gradient was higher (~8-14 MV/m), limited by available RF power due to low Q. Some DC current was observed from a pick-up antenna at gradients higher than 11 MV/m. After increasing the tuning gap in the lower HOM coupler by 0.2 mm, the Q at high field operation was increased by a factor of two and an accelerating gradient of 14 MV/m was achieved, most likely due to the increased resonance frequency of that HOM coupler.

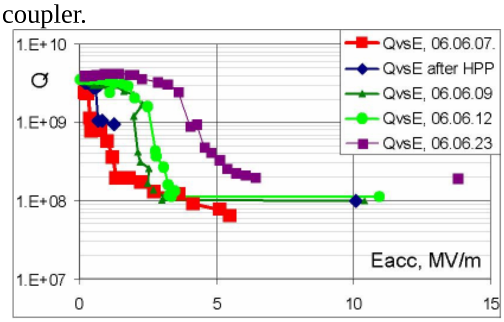

Figure 2: History of the Q vs. E measurements.

"0"-mode measurements showed a fairly high Q up to the quench level (Fig. 3). Fields in the end cells of the cavity are much lower in this mode. The result clearly indicates that the problem is located in the cavity ends,

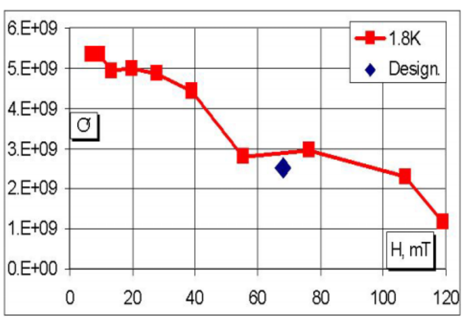

Figure 3: Q vs. surface magnetic field for "0"-mode.

not in the cells. Also, some x-rays were observed in higher field operation.

A temperature sensor installed in one of the HOM couplers showed heating during the pulse. In CW operation with a power level of ~100 W the temperature at the sensor increased ~20 K in one minute.

After the high power test, visual inspection of the HOM couplers showed a gap between the curved leg of the form tile and the HOM can near the weld joint. More detailed analysis revealed that 1st leg of the form tile was completely separated from the can (Fig. 4). To understand which step of cavity production and preparation resulted in this damage we started different tests. Several tests such as BCP, cold shock, and HPR were done to explain the mechanism of the failure. So far none of these investigations can give us a clear picture of the reason for the damage.

One possible failure mechanism is thermal stresses. Dynamic calculations for warming up and cooling down show results very similar to the temperature measurement data from the cold test. Thermal and stress analyses show a possibility to reach stresses close to the yield point.

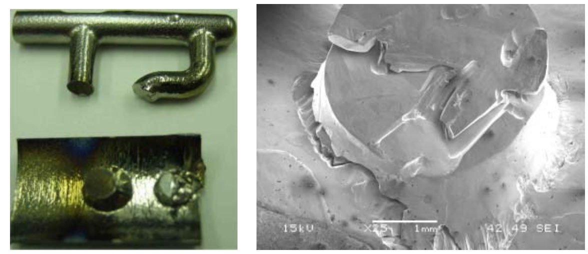

Figure 4: Curved leg of the HOM form tile fractured from HOM can.

Initial heating starts as a result of multipacting (Fig. 5). When the form tile surface reaches normal-conducting temperature, the surface resistance increases dramatically and it results in additional power loss in the form tile. The outside surface of the HOM can stays cold because it is cooled by the surrounding superfluid helium. Significant temperature difference and associated thermal extension could result in enough stress to cause damage [7].

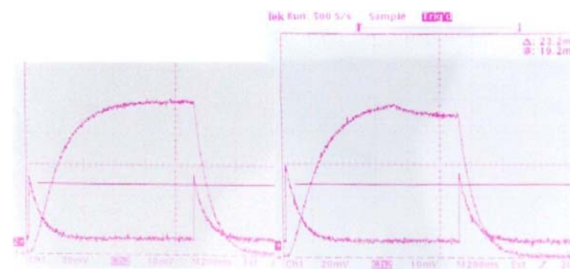

Figure 5: Transmitted and reflected power signals just before (left) and after (right) 1st multipacting starts.

NEW HOM COUPLER DESIGN

We started a design of a new HOM coupler (Fig 6). The new RF design should eliminate several identified problems such as:

- Multipacting near the welding joints and tuning gap
- The 2nd main resonance of the HOM being very close to the operating frequency, which results in high fields in the HOM at 3.9 GHz.

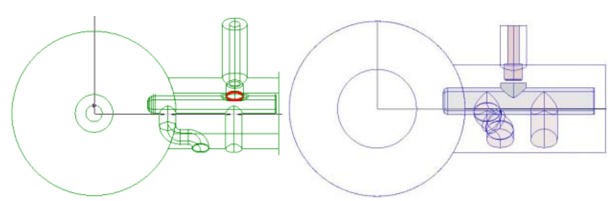

Figure 6: Old (left) and new (right) design of HOM coupler.

It is also necessary to decrease the electric and magnetic fields in the HOM at 3.9 GHz, to decrease heating of the antenna tip, and to decrease sensitivity to thermal deformations. Increasing the leg diameters will eliminate full melting of the legs during welding.

A new full-size solid model of the 9-cell cavity with two HOM couplers and a main coupler was used for the external Q calculation. Figure 7 shows the calculated Qext for the 1st, 2nd, 3rd, and 5th passband modes. For the modes with the largest R/Q (Fig. 8), Qext is typically less than 1e5, which is the threshold defined by BBU calculations.

We are going to build a copper model of the redesigned HOM coupler and measure its properties in a full-size copper model 9-cell cavity. On this model the Qext of the HOM coupler can be determined and optimized for different positions of the HOM relative to the cavity and the main coupler. In addition, calculations for different designs of the HOM coupler will be continued.

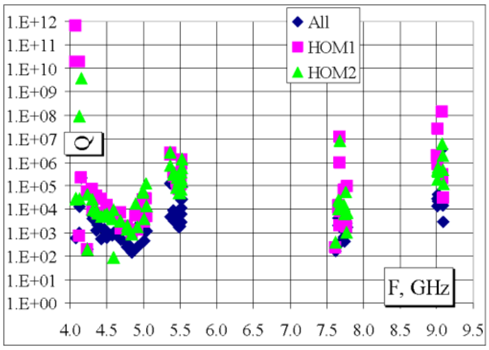

Figure 7: Qext calculated for the 9-cell cavity with a main and two HOM couplers.

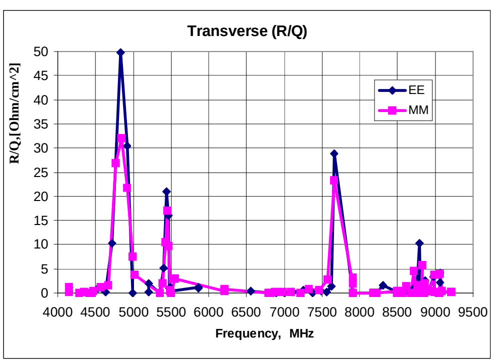

Figure 8: Calculated R/Q for the 9-cell cavity.

SIMULATIONS OF MULTIPACTING IN THE HOM COUPLER

Preliminary 3D multipacting (MP) calculations show a possible problem in the HOM coupler in the range of ~10 mT surface fields at the inner conductor (Fig. 9). MP activity is very sensitive to the shape of the conductor; for example, increasing the gap between the conductor and the HOM body will eliminate MP in the full design field range. This modification can hopefully be done without rebuilding the HOM coupler.

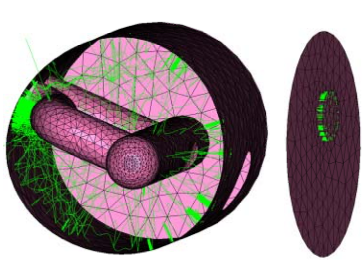

Figure 9: Resonant particle trajectories in the old design of HOM coupler.

For simulations of multipacting phenomena in the HOM coupler we used a recently developed extension to the 3D computer code ANALYST [8]. In Figure 8 all detected resonant trajectories are presented. The simulations show the presence of possible multipacting at different field levels. One-point multipacting on the HOM coupler body and two-point multipacting between the form tile and the cylindrical part of the coupler occurs at E_{acc} = 11.2, 11.8, 12.1, 13.5 MV/m (Fig. 9 left). Two-point multipacting occurs in the tuning gap at E_{acc} = 0.55-0.8 MV/m.

To avoid multipacting in the described areas a new profile of form tile has been designed (described above). Only a few resonant trajectories were found (Fig 10), but the impact energy is not enough for MP. The simulations show that in the new design we succeed in avoiding multipacting in the tuning gap. On the HOM coupler body, we do not observe the two-point multipactingbut still have the one-point multipacting.

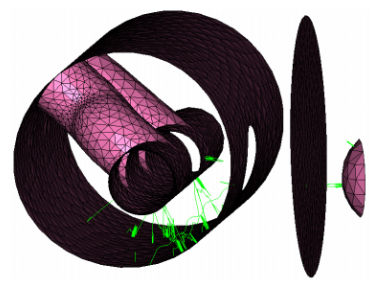

Figure 10: Resonant particle trajectories in the new design of HOM coupler.

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