

# Production and test results of SC 3.9-GHz accelerating Cavity at Fermilab

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**Abstract**— The 3<sup>rd</sup> harmonic 3.9GHz accelerating cavity was proposed to improve beam performances for TTF-FEL facility. In the frame of collaboration Fermilab will provide DESY with a cryomodule containing a string of four 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 this paper we discuss the status of the cavity and coupler production and the first result of cavity tests. It is hoped that this project will be completed during the first half of 2007 and the cryomodule delivered to DESY in this time span.

**Index Terms**— Superconducting accelerator cavities, multipactor, testing, coupler.

## I. INTRODUCTION

The construction and successful test of key components: copper and niobium cavity prototypes, helium vessels and blade-tuner, allowed us to start cavity production after several minor modifications in design. The overall objective is to build eight 3rd harmonic cavities. The first three cavities are completed. The rest of the cavities are under production at JLAB and Fermilab. All of the necessary pieces for cavities 4-6 are at JLAB and will be assembled when requested. Dumbbells for cavities 7 and 8, to be built at Fermilab, are also complete except for trimming.

Six power couplers received from CPI, were inspected and one of them assembled with 9-cell cavity for Q measurements. The status of coupler inspection and test stand for coupler processing is discussed below.

Cavity #1 fabrication was completed in Dec. 2005 and processing was carried out until a failure of one HOM tuning membrane occurred during an ultrasonic rinse following the initial inside surface etch. These membranes have since been redesigned to a greater thickness.

Cavity #2 has received the most extensive processing. It was also suffered an HOM failure, however, it occurred during vertical performance testing when the leading leg of the formteil in both HOM couplers fractured due to high temperature heating caused by multipactoring and RF heating. The analysis of failure is discussed below.

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## II. STATUS OF MAIN COUPLER

### A. Input Coupler and Test Stand Status

Six input couplers were received from the vendor in June 2006. Many of the components failed to pass quality control checks. From a total of eighteen subassemblies, four are found to have vacuum leaks; two brazed joints, one welded joint, and one damaged sealing knife edge on a Conflate-style vacuum flange leak. Copper plating on stainless steel conductors is found to be unsatisfactory on three other subassemblies due to blistering of the plating from the surface. Additionally, there is one cold end assembly with an approximately 0.4mm gap in a brazed joint which is designed to be tight. Simulations are ongoing to understand whether this component is acceptable.

It is expected that the vendor will quickly repair and return the deficient components. In the mean time, there is a sufficient number of each component to assemble two complete couplers and proceed with testing of antenna coupling and high power coupler conditioning.

All components for the test stand are in-house. The first tests are expected in early September 2006.

### B. Input Coupler Qualification and Test

Input coupler quality control includes visual inspection, mechanical measurements, and leak check of all subassemblies. Couplers are then tested and antennas are trimmed for proper cavity coupling. Finally, the couplers undergo high power RF cycling to condition and test them for proper performance.

All inspection reports are recorded in a database. The visual inspection includes an examination of copper plating, checks of threaded holes, flange orientations, sealing surfaces,



Fig. 1. Cold End Assembly on CMM and coupling test of the input coupler.

and overall workmanship. A CMM is used to check that couplers meet mechanical tolerances specified on the prints (Fig.1).

Antennas are procured 1mm longer than the length suggested by simulation to accommodate assembly tolerances and any analysis error. Since the coupler antenna length is not adjustable, the final length will be done by trimming antenna by wire EDM, after measurement of a coupler mounted on a bare cavity at room temperature.

Coupler conditioning with high power RF is the final qualification test. Before test, all components are cleaned in ultrasonic wash and rinse cycles, dried and assembled on to the test stand in class 10 (the cold parts) and class 100 clean rooms, and in-situ baked at 150C for 24hours. Couplers are tested in pairs up to 80kW power pulses increasing in duration to a maximum of 1.3ms. During this conditioning cycle, couplers are under vacuum, while vacuum level readouts determine the conditioning rate. The test is expected to last 2-3 days per coupler pair.

### III. HIGH POWER TESTS

#### A. Prior results of the 3-cell cavity

The 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 first test showed a field emission problem, which was fixed after appropriate high pressure rinsing. The achieved residual surface resistance was  $\sim 6n\Omega$ . The cavity was quenched at accelerating gradient of  $\sim 19$  MV/m (surface magnetic field of  $\sim 105mT$ ), which corresponds  $\sim 21MV/m$  in 9-cell cavity, limited by thermal breakdown. The results of the cold tests were reported in papers [1-2].

#### B. Test results of the 9-cell cavity

Cavity #2 was successfully manufactured, tuned and tested after BCP, high temperature treatment and HPWR. Initial measurements at low field (Q vs. T) showed a very high

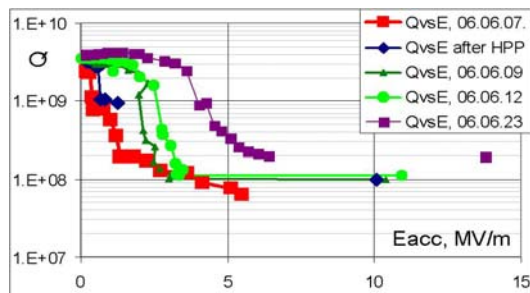


Fig. 2. History of the Q vs. E measurements.

residual resistance  $\sim 3000$  n $\Omega$ , but after high power processing, the residual resistance dropped off  $\sim 40$  n $\Omega$ . The history of Q vs E measurements is shown in Fig. 2.

In the cavity tests we observed strong multipactoring (MP), which causes Q-slope even at low field. After high fields “processing” Q improved for small fields and the MP level shifted from  $\sim 0.5$  MV/m accelerating gradient to  $\sim 4$  MV/m in CW regime. In pulsed regime accelerating gradient was higher

$\sim 8-14$  MV/m, limited by available RF power due to low Q.

“O”-mode measurements shows fairly high Q up to the quench level. 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, not in the cells.

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

After few high power tests, the visual inspection of the HOM couplers showed a gap between the curved leg of the formteil and the HOM can near the weld joint. More detailed analysis revealed that 1<sup>st</sup> leg of the formteil was completely separated from the can (Fig. 3). To understand which step of cavity production and preparation resulted in this damage we started different tests, such as BCP, cold shock, and HPR. So

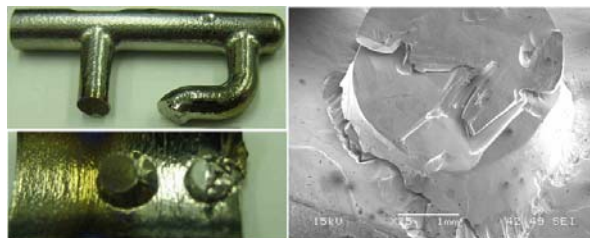


Fig. 3. Curved leg of the HOM formteil fractured from HOM can. far none of these investigations can give us a clear picture of the reason for the damage. The failure mechanism is most likely thermal stresses, discussed below in more details.

### IV. SIMULATIONS OF MULTIPACTING IN THE HOM COUPLER

Experimental data clearly shows strong MP activity in the HOM coupler. To simulate MP a recently developed extension to the 3D computer code ANALYST was used. The results of calculation show a possible problem in the HOM coupler in the range of  $\sim 10$  mT surface fields in formteil: one-point MP on the HOM coupler body and two-point MP between the

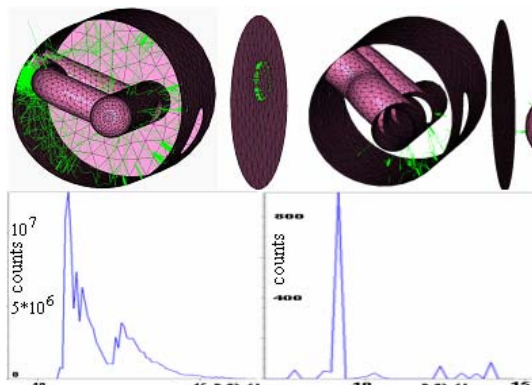


Fig. 4. Resonant particle trajectories in old (left) and new (right) designs of HOM coupler.

formteil and the cylindrical part of the coupler occurs at  $E_{acc} \sim 11-13$  MV/m (Fig. 4 left). Two-point MP occurs also in the tuning gap at low accelerating fields:  $E_{acc} \sim 0.55-0.8$  MV/m.

To avoid MP in the described areas a new profile of formteil has been designed (described below). Only a few

resonant trajectories were found in a new design, but the impact energy is not enough for MP. In the tuning gap no resonant trajectories were found. On the HOM coupler body, we do not observe the two-point MP but still have the one-point MP, which is a few order of amplitude weaker than in existing design.

### V. THERMAL STRESS ANALYSIS.

Following its fourth cold test, cavity #2 was opened for visual inspection in an attempt to find indications of MP. It was discovered that one leg (dog leg) of the F-piece antenna had been fractured completely through. Inspection of the other leg revealed a fracture though not as severe.

Physical analysis of the failure is being carried out both under Fermilab auspices and at DESY. One of the broken formteils and a sample piece has been sent to DESY and we are also awaiting testing results from a nearby analysis laboratory. SEM analysis has already been done at Fermilab, which also shows cracking at the base of the weldment (Fig.3).

Initial heating starts as a result of MP. When the formteil surface reaches normal-conducting temperature, the surface resistance increases dramatically and it results in additional power loss in the formteil. The outside surface of the HOM can stay cold, cooled by the surrounding superfluid helium. Significant temperature difference and associated thermal extension could result in enough stress to cause damage [6].

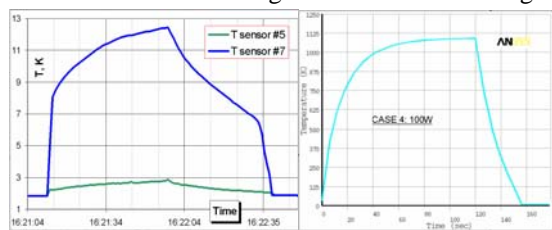


Fig. 5. Measured (left) and calculated (right) temperature profiles.

Dynamic calculations for warming up and cooling down show results very similar to data the temperature measurement from the cold test (Fig.5) Thermal and stress analyses show a possibility to reach stresses close to the yield point.

#### A. FEA results

Recent analysis, though not fully conclusive, indicates that the failures are likely due to high stresses induced by overheating of the formteil when power is applied, most likely caused by multipacting. Finite element analysis (FEA) of the formteil indicates high local thermal stresses at the exact same location where the fractures occurred (Fig. 6).

The fact that the maximum stress always occurs at this same critical location for different heating scenarios indicates that this ‘weak spot’ is a characteristic of this particular geometry. The max principal and shear stress are always compressive at this location, and the 3<sup>rd</sup> principal stress at 100W was found to exceed the tensile strength of Nb at 100K. Although 100W CW might seem like an unlikely scenario for the formteil, even at lower power levels fatigue at brittle temperatures could cause failure at much lower stresses than the yield due

to thermal cycling. The failed specimens will thus be investigated for signs of a fatigue failure. The brittle behavior of Nb at cold temperatures should also be investigated, especially in compression. Future FEA work includes

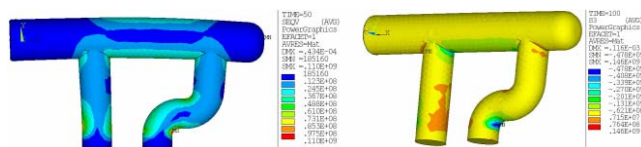


Fig. 6. Von Mises equivalent stress (MPa) in formteil at 50W power and 100W -478MPa exceeds ultimate strength of Nb at 100K.

simulating the e-beam weld on the formteil-HOM assembly to evaluate residual stresses during cooldown. This might help explain cracking at the base of the weld recently discovered from the SEM analysis.

### VI. NEW HOM COUPLER DESIGN

We started a design of a new HOM coupler (Fig 7). The

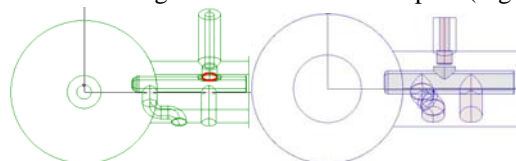


Fig. 7. Old (left) and new design of HOM coupler.

new RF design should eliminate several identified problems such as: 1) MP near the welding joints and tuning gap; 2) the 2<sup>nd</sup> main resonance of the HOM being very close to the operating frequency, which results in high fields in the HOM at 3.9 GHz.

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. Calculated Qext is less than 10<sup>5</sup> (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.

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