DEVELOPMENT OF THE THIRD HARMONIC SC CAVITY AT FERMILAB

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Abstract

The third harmonic 3.9 GHz superconducting cavity was recently proposed by DESY for a new generation of high brightness photo-injector (TTF photoinjector-2) to compensate nonlinear distortion of the longitudinal phase space due to RF curvature of the 1.3 GHz TESLA cavities [1,2]. Installation of the 3rd harmonic cavity will allow us to generate ultra-short (<50 µm rms) highly charged electron bunches with an extremely small transverse normalized emittance (<1 µm). This is required to support a new generation of linear colliders, free electron lasers and synchrotron radiation sources. In this paper we present the current status of the 3rd harmonic cavity being developed at Fermilab. We discuss the design procedure, the building and testing of the copper and niobium half-cells and components, the design of input and HOM couplers.

INTRODUCTION

The design philosophy of producing highly charged bunches is based on using a long laser pulse to pull a long bunch from the photocathode and thereby reducing the deleterious space charge effect. However, in the accelerating section, the sinusoidal accelerating field profile distorts long bunches. The purpose of the 3rd harmonic de-accelerating section is to compensate for this distortion. In this manner, the injector should generate nC-bunches at an emittance that is four times lower than what existing injectors typically produce.

Fermilab, as part of the TTF collaboration, participates in developing and testing 3rd harmonic cavities at the existing FNPL photoinjector [3]. A number of USA institutions have expressed interest in specific facets of the photoinjector program and intend to form a collaboration to build and operate a 100+ MeV high-brightness electron photoinjector at Fermilab.

CAVITY DESIGN

Design parameters

The first design of the 3.9 GHz cavity was proposed by DESY[4]. The cavity consists of nine cells with an elliptical cup shape with a 30mm diameter iris and a 40mm diameter beam pipe. However, Fermilab calculations done for this design show that the coaxial input coupler has to be mounted very close to the end cell to provide the necessary coupling. In an improved design, the iris diameter of the end-cell was increased to 40mm with increased distance from the end-cell to the input coupler (Table 1). This leaves more space for welding and mounting of the helium vessel flange. The field distribution in the half-cavity is shown in Fig.1. The design parameters of the 3rd harmonic section are presented in Table 2.

Table 1: Geometry of the cups.

Dimensions in mm	mid-cell	end-cell
Iris radius, *a*	15.0	20.0
Equator radius, *b*	35.787	35.787
Half-cell length, *h*	19.2167	19.2167
Curvature at:		
Equator–horz/vert semi-axis	13.6/15.0	14.4/15.0
Iris - horz/vert. semi-axis	4.5/6.0	4.5/6.0

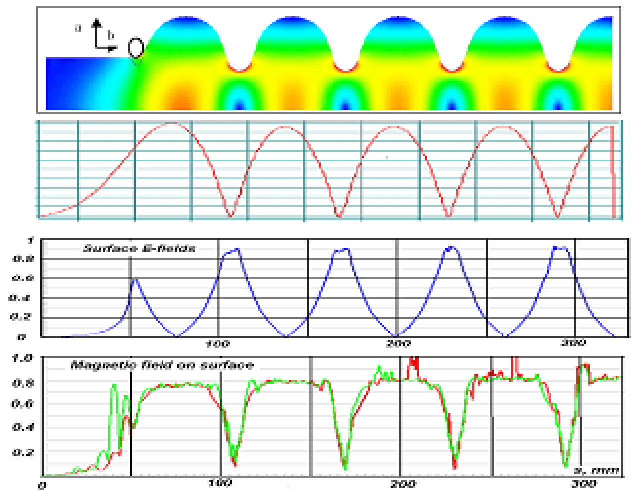

Fig.1. E-field (from the top: in cavity, on axis and on surface) and H-field on surface (bottom). HFSS.

Table 2: 3.9 GHz section parameters.

Number of cavities		4
Active Length	m	0.346
Gradient	MV/m	20
Phase	degree	-179
R/Q	Ohm	375
Q_{ext} for accelerating mode		9.5e+5
BBU limit for HOM, Q		<1.e+5
Total energy	MeV	20
Beam current	mA	9
RF power/per cavity	kW	11.5

Lorentz forces

Lorentz forces, caused by electromagnetic fields, may change frequency during the RF pulse. An ANSYS analysis, made for niobium half-cells with fixed boundaries, shows frequency shift of 90Hz for a 2.8-mm thickness and ~200Hz for a 1.5mm thickness. (Fig.2). Electric and magnetic surface fields were taken from HFSS calculations. If free boundaries are assumed, then the frequency shift will be one order of magnitude higher. However, comparison calculations with the experimental results for TESLA and CKM cavities show, that the fixed boundaries assumption is more realistic. These calculations show that the rigidity of the cavity, fabricated from 2.8mm thick niobium is high enough, even without stiffening rings.

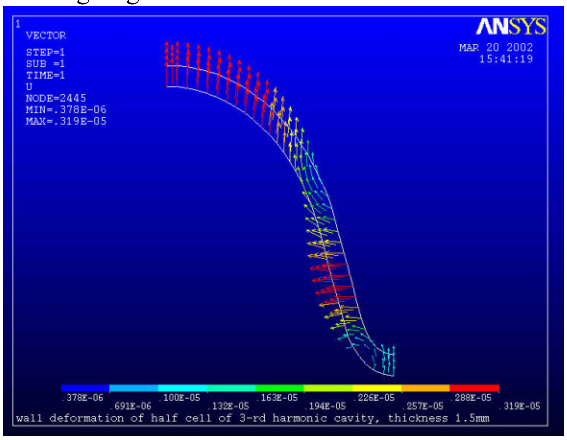

Fig.2. Distribution of surface displacement.

FABRICATION OF COMPONENTS

Forming of half-cells

For cup production two different processes are under development. For the conventional deep drawing process, we built a set of dies, machined from 7075-T6 aluminum alloy and formed the cups, using 2.8-mm-thick niobium (RRR 300+) or copper blanks. (Fig.3). To get the required curvature at the iris, the nose of the cup is then coined [5]. An alternative process is hydro-forming of the cups. Advanced Energy Systems, Inc. is developing this process for the 3rd harmonic and CKM cavities.

Fig.3. Tooling. Copper and niobium half-cells.

Using the deep drawing technology, many copper and niobium cells have been produced. The shape was carefully monitored on a CMM machine. First results show large profile errors of ~200µm, predominately near the iris, where the radius of curvature is only 4.5 mm. This deviation causes a frequency error of ~15 MHz. The best and repeatable results were achieved by intermediate annealing followed by re-coining and re-stamping (Fig4.). All 22 copper and 6 niobium cups, produced with this improved technology, have < 1MHz dispersion in frequency. The actual frequency is well correlated with the length of the cell.

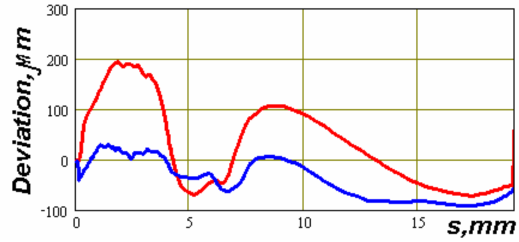

Fig.4. Deviation from design shape after drawing+coining (red), and following annealing+coining+drawing (blue).

Welding of Dumbbells

Twelve niobium cups were formed to help develop the forming and welding technology. Electron-beam welding parameters were optimized for iris and equator welds (Fig.5). The measured weld shrinkage was ~0.3mm/joint at the iris and ~0.2mm/joint at the equator with deviation of ±10%. Annealed half-cells had higher shrinkage, but more tests are needed to finalize EBW characteristics.

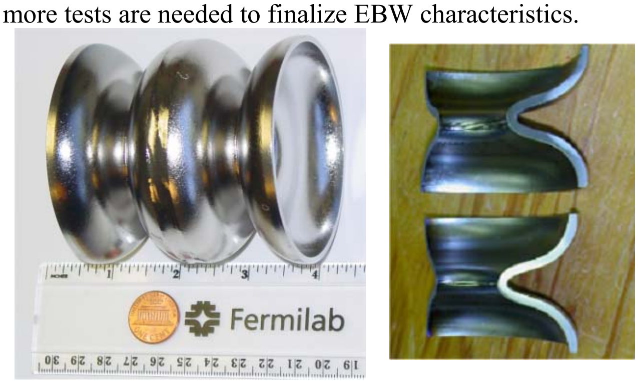

Fig.5. Welded dumbbells

Cavity tuning

After fabrication, the cavity has to be tuned to obtain the design frequency and field flatness. Limitations in the space between cup pairs, makes it difficult to use a conventional tuning system. A more adequate solution is obtained by squeezing the equator diameter instead of changing the cell length [6]. This type of tuner was designed, built and tested (Fig.6). The tuning clamp consists of 8 curved steel sectors, sliding on a chain. The chain length can be adjusted by a screw. Since the inner surface of this clamp conforms to the cell shape, longitudinal lengthening of the cell is minimal. During the test, a niobium cell was easily tuned up to 35 MHz, which is a higher than our goal.

Fig.6. Frequency tuning device.

Copper model

Building a copper model is the first step in developing fabrication, tooling, RF control and tuning. Copper and niobium have similar mechanical properties, but copper is cheaper and has a higher conductivity at room temperature. A general view of the copper model and some components are shown in figure 7.

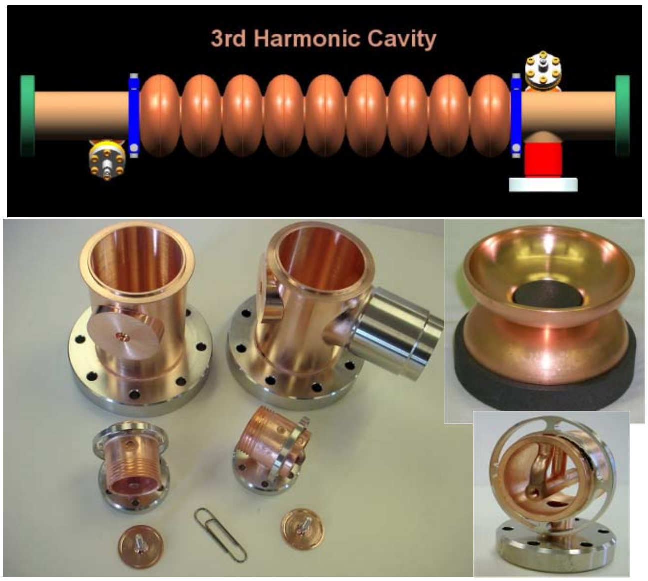

Fig.7. Cavity, end-tubes, dumbbells and HOM couplers.

End-tubes are decoupled from the cavity body to give us the ability to rotate or replace components if needed. HOM couplers are also rotatable. Measured RF properties of the coupler are in a good agreement with the calculations. All components are brazed, tested and ready for final brazing.

Input coupler

Fig.8 shows the design of the coaxial, adjustable input coupler, we are developing for 3.9GHz cavity. This is 50Ω coaxial line with a 30mm outer diameter to prevent the excitation of asymmetrical modes. For the cold window, we adopted the cylindrical ceramics of TESLA's coupler. For the warm window we are planning to use a standard waveguide window designed by CPI for a 3.9 GHz klystron.

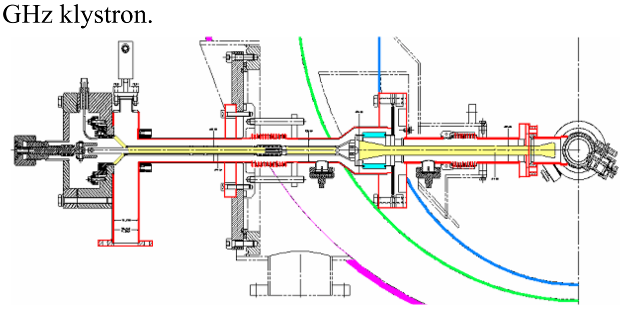

Fig. 8. Coaxial input coupler.

The coupler has pick-ups and light detection and is designed with DC biasing to suppress multipactor (MP). A lower power level should facilitate MP problems, but we need more detailed calculations to prove this statement. Bellows, in the assembly, allow us to move the antenna back and forth (±2.5mm) and adjust Qext by a factor of five. The current design is quite complicated and after a discussion with W.D. Moller, we are working on a simple non-adjustable version of this coupler.

HOM analysis

Trapped High Order Modes (HOM) may excite BBU instability in the accelerator. Beam dynamics analysis gives us an upper limit of Qext (Table.2). Using HFSS, we have analyzed high order modes in 2-D model (R/Q calculations) and 3-D (R/Q and $Q_{external}$) up to 9 GHz [7,8]. 3-D geometry includes the input coupler and two HOM couplers with mirrored symmetrical antennas. The cavity in this model is excited by the beam with 2 mm vertical or horizontal off-sets. Analysis shows that if we apply electric or magnetic boundaries at the end of cavity, then few modes in the third passband have Q_ext above the BBU limit. For a more realistic assumption, "open" boundaries, all dipole modes in three first pass-band will be significantly damped with the maximal Q_{ext}=2400 (figure 9).

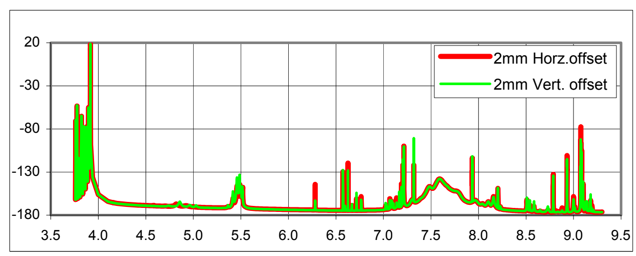

Fig.9. Field amplitude in cavity (dB) vs. frequency (GHz).

CONCLUSION

Fermilab is making good progress in developing a superconducting 3.9 GHz accelerating cavity [9].

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