DEVELOPMENT OF THE 3.9 GHZ 3RD HARMONIC CAVITY AT FNAL

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Abstract

Peak current and emittance of the high brightness photoinjector are limited by non-linear energy distribution in the bunch. Adding a weighted amount of third harmonic accelerating voltage allows compensate this non-linearity. For FNAL-NICADD photoinjector it can result in significant improvement of its performance reducing emittance and increasing peak current. These benefits have triggered designing and prototyping of a superconducting 3.9 GHz (3rd harmonic to 1.3GHz used as a main accelerating frequency) cavity at FNAL.

At first stage it was built two models: 9-cell copper cavity and 3-cell niobium cavity. In this paper the status of the cavity design and results of RF measurements of the two models are presented.

INTRODUCTION

Third harmonic cavity initially was proposed to improve performances of TTF/DESY photoinjector [1-3]. Fermilab, as part of the TTF collaboration, participates in developing 3rd harmonic cavity and testing it on the existing FNPL photoinjector [4]. The goal is to install cavity and study it performances at Fermilab and build cryostat with four cavities for installation on TTF/DESY.

CAVITY DESIGN

Cavity consists of nine cells with elliptical cup shape with 30mm iris diameter and 40mm beam pipe diameter (fig.1). TTF-III photoinjector requires section of four such a cavities with the parameters shown in table

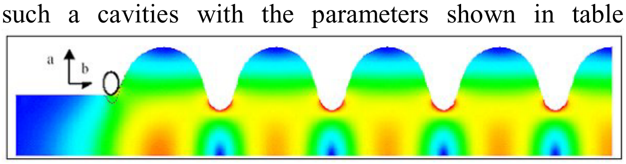

Fig. 1: E-field distribution in half-cavity.

Table 1: Parameters of the 3rd harmonic 3.9 GHz section.

Number of cavities		4
Active Length	m	0.346
Gradient	MV/m	14
Phase	degree	-179
R/Q	Ohm	375
Qext 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

Fig. 2 shows cavity design. Cavity, made of 2.8mm niobium is rigid enough even without stiffening rings. Calculated frequency shift due to Lorentz forces is 90 Hz, which is small to compare with cavity pass-band.

To prevent beam instability, high order modes (HOM) have to be well dumped. Two HOM couplers with appropriate mutual orientation are mounted on both ends of the cavity to provide enough dumping for both polarizations of dipole modes and other HOMs [5]. Design of the HOM couplers is similar to DESY design, scaled to 3.9 GHz.

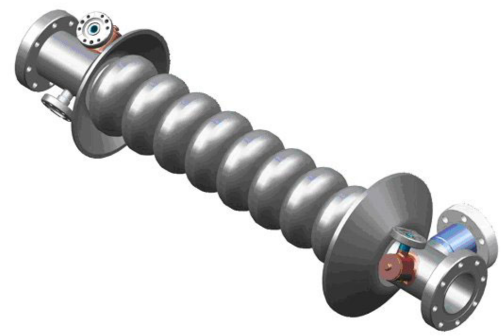

Fig. 2: Cavity design.

HIGH ORDER MODES IN CAVITY

HOM properties in the 3rd harmonic cavity were studied in papers [6,7]. For the small beam displacement the major contribution to BBU instability comes from the dipole modes. The amplitude of dipole mode depends of R/Q and Q external. External Q-factor was calculated by using HFSS model, which included cavity, main coupler and two HOM couplers. Cavity was excited by the beam, which in HFSS model was represented by the numbers of small antennas with the current, installed in each cell. Phase advance between them was chosen such a way to approximate relativistic electron beam. Antennas shifted 2mm off-axis in x or y directions allow excite both polarizations. The result is very sensitive to the boundary conditions at the ends of the cavity. For electric or magnetic boundaries, Q external exceed BBU limit (from the table) for a few dipole modes in 2nd, 4th and 5th pass-bands (fig.3). In case of radiation boundaries, only one

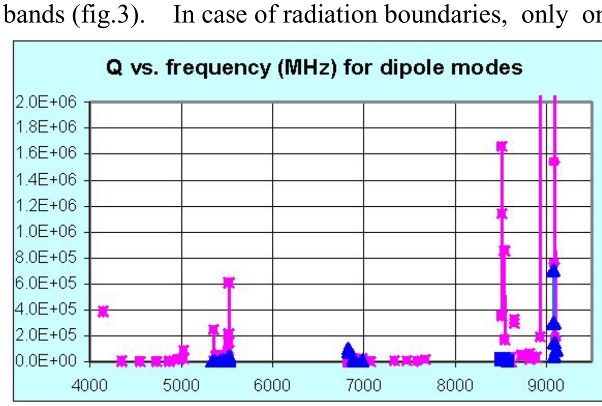

Fig. 3: External Q-factor calculated for electric-electric (pink) and magnetic-magnetic (blue) boundaries in cavity.

mode with Q_{ext}=1.1*10^5 was found in the 5th pass-band. This mode is trapped in the cavity, having small fields in the beam tubes. Bead-pull measurements made in copper model confirm our simulations (fig.4).

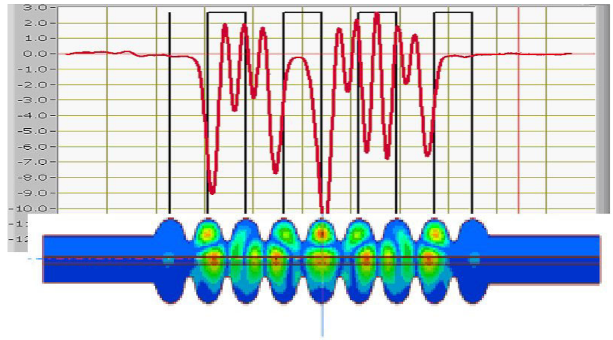

Fig. 4: Trapped mode in 5th dipole band measured in copper model. F=9029 MHz. Q=32000.

It is not clear what real value of Q_{ext} will be in chain of cavities, when part of radiated power will be reflected back from the next cavity after some dissipation in bellows and couplers on the way. We can answer this question after finishing second copper cavity and measuring HOM in whole assembly. We also need quantify more carefully BBU limits for each mode independently.

DESIGNING

Input Coupler

Fig.5 shows preliminary design of the coaxial adjustable input coupler, developing for 3.9GHz cavity. Our design is based on of TTF-3 coupler, but has smaller outer diameter 30mm to prevent excitation of asymmetrical modes. For the cold window we adapted cylindrical ceramics of TESLA coupler, as for the warm window, we are planning to use waveguide window, designing by CPI for 3.9GHz klystron. Coupler is equipped with pick-ups electrodes and light detector and designed with DC biasing to suppress multipactor (MP). Bellows allow us move antenna forth and back (±2.5mm) and adjust Qext by factor of 5.

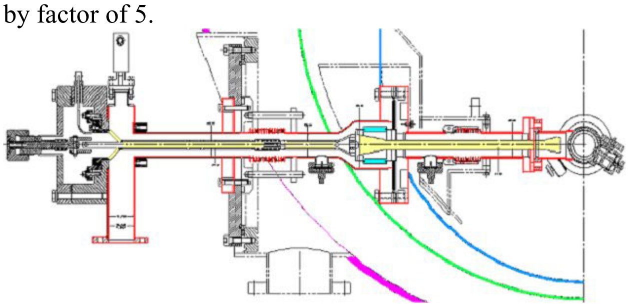

Fig. 5: Design of the input coupler.

Smaller outer diameter makes assembly, alignment and cleaning of coupler more complicated than in DESY design. After discussion with the DESY group it was decided to build simple non-adjustable version of this coupler, taking into account low power level needed for 3rd harmonic cavity and adjust coupling by three-stub waveguide tuner. Lower power (~10kW) and high frequency should also facilitate MP problems. Simulations done for the cold cylindrical window (Multipac2 code) show that MP threshold is a few hundred kW.

Other Components

Most of the designed components (cavity, HOM coupler, helium vessel, blade tuner etc.) as well as cavity and cryostat layouts are presented in [8] and website [9]

FABRICATION

Forming Half-Cells

Cavities for warm tests are fabricated by brazing together copper half-cells. Superconducting cavities will be fabricated by joining niobium half-cells via electron-beam welding. The half-cells are formed from 2.8 mm thick copper or niobium blanks. Strict mechanical and electrical tolerances are imposed.

Two approaches are under investigation. Half-cells are formed at Fermilab (FNAL) by deep-drawing, while Advanced Energy Systems (AES) has been contracted to produce cavities using a hydroforming process. In both approaches the half-cells are then coined at the iris to achieve the required curvature. At FNAL the copper half-cells are annealed after initial forming, then they are re-coined and re-drawn in reverse order. Critical factors that are required to be controlled are: (1) Half-cell length and the shape of the RF surface, (2) Circumferential uniformity of individual half-cells, and (3) Repeatability of inner surface shape from half-cell to half-cell.

From each batch of half-cells several are selected for inspection. Using a coordinate measuring machine (CMM), the inner surface of each half-cell is profiled along axial planes at 0, 90, 180 and 270 degrees (A,B,C and D on fig.6). To check circumferential uniformity the deviation from design shape as a function of axial displacement from all four sets of CMM data for individual half-cells can be compared, as shown below on fig.6. Repeatability is verified by observing the deviation from design shape for CMM measurement data from a statistically significant number of half-cells.

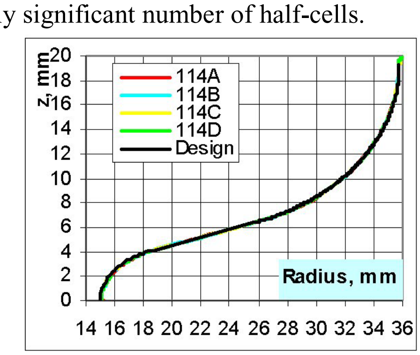

Fig. 6: Result of half-cell profile measurements.

Dumbbells

Dumbbells are formed by brazing (copper) or electron-beam welding (niobium) half-cells at the iris. Brazing does not present the problems of shrinkage and distortion that are inherent in the electron-beam welding process. Niobium half-cells are held in a welding fixture that is designed to insure that their equatorial planes are as close to parallel as possible after welding, while still allowing freedom for weld shrinkage in the axial direction.

The RF surface of each dumbbell is inspected as previously using the CMM. Critical factors to be controlled are: (1) Shrinkage at the iris, (2) Tilting of the equatorial planes, and (3) Loss of circumferential symmetry at the iris due to welding distortion. Iris shrinkage can be predicted statistically. Tilt can be somewhat influenced by the design of the welding fixture, but also appears dependent on material thickness (dumbbells formed from thicker niobium appear to exhibit less tilt). Tests are underway at FNAL to improve circumferential symmetry at the iris by determining the optimum electron-beam welding current profile.

PROTOTYPES AND TEST RESULTS

Copper 9-Cell Cavity

Copper model was fabricated by brazing together half-cells. For flexibility beam tubes are made decoupled. HOM couplers are mounted on rotational flanges, which allow us change their orientation. After fist iteration of tuning the initial error in field flatness ~15% was reduced to <1% (fig.7). For cell-to-cell tuning we have built a special tuner that changes cell frequency by squeezing equator diameter.

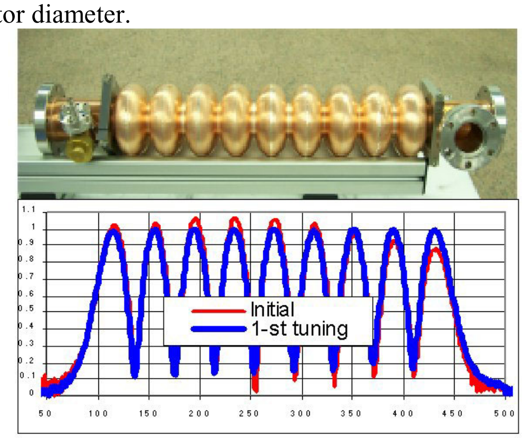

Fig. 7: Copper model and result of flatness tuning.

After matching the HOM coupler rejection frequency, all HOM characteristics in cavity were carefully measured.

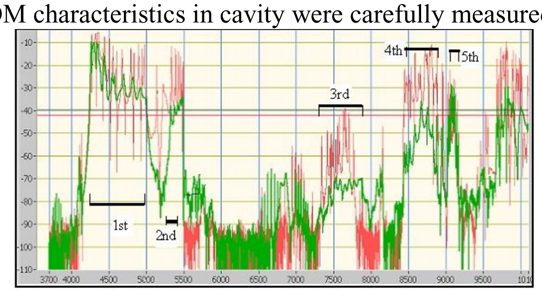

Fig. 8: S12 (dB) HOM1 to HOM2 in 9-cell cavity. Green line - beam pipe opened. Red line – shorts in.

We were looking for the modes with high Q external and measured field distribution Figure 8 shows power transmission through the cavity for open and shorted beam pipes. One can see considerable difference in the amplitude and Q-factor in those cases.

Niobium 3-Cell Cavity

Using developed technology, the simple 3-cell niobium cavity was built for studying RF performances in the vertical cryostat (fig.9). Cavity will be excited by coaxial antenna with adjustable coupling. Pick-up antenna from the other side of cavity will control field and Q-factor. Length of the beam pipes is made long enough to exclude power dissipation in flanges and antennas. Field flatness in cavity and frequency has been tuned the same way as for copper model. All components are ready and will be assembled and tested after BCP of cavity.

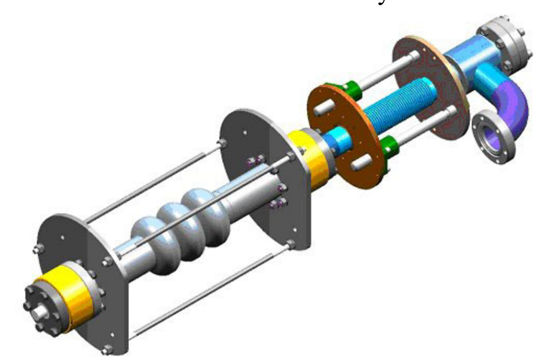

Fig. 9: Assembly of the 3-cell cavity for the cold tests.

SUMMARY

Fermilab made progress in engineering and designing 3rd harmonic cavity (3.9 GHz). We have built and tested HOM coupler and copper full-scale cavity. Niobium 3-cell cavity is ready for cold tests in vertical cryostat.

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REFERENCES

[1] M.Ferrario *et al.*, TESLA-FEL-01-03.
[2] F.Floettmann *et al.*, TESLA-FEL-01-06.
[3] J.Sekutowicz *et al.*, TESLA-FEL-02-05.
[4] J-P.Carniero *et al.*, "First results of the Fermilab high brightness RF photoinjector", Proc. PAC99, p.2027.
[5] M.Dohlus *et.al*, TESLA 2002-05.
[6] N.Solyak, et al., Development of the 3rd harmonic SC cavity at Fermilab, PAC2003, Portland, May 2003.
[7] T.Khabiboulline *et.al.*, HOMs of a 3rd harmonic cavity with increased end-cup iris, FERMILAB-TM-2210, 2003
[8] M.Foley, T.Khabiboulline, D.Mitchell, N.Solyak, Mechanical design and engineering of the 3.9 GHz, 3rd harmonic SRF System at Fermilab ". This proceedings.
[9] http://www-td.fnal.gov/lc/sc/lc.html