DESIGN, PROTOTYPE AND MEASUREMENT OF A SINGLE-CELL DEFLECTING CAVITY FOR THE ADVANCED PHOTON SOURCE*

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Abstract

After the design optimization of a squashed elliptical shape, single-cell, superconducting (SC) deflecting cavity at 2.815 GHz, a copper prototype has been bench measured to determine its rf properties and the effectiveness of waveguide damping of parasitic modes [1]. RF cold tests were also performed at 2K on niobium single-cell and two-cell prototype cavities. Details of impedance calculation using wakefiled analysis of the single-cell cavity are shown to meet the strict 200 mA beam stability requirement of the Advanced Photon Source (APS) at Argonne National Lab where a total of 16 single-cell cavities will be divided into two cryomodule. The design of higher-order mode (HOM) waveguide damping, the simulations of the Lorenz force detuning, and the prototype of on-cell damping are presented.

INTRODUCTION

An RF deflecting cavity used to chirp electron bunches to impose a quasi-linear correlation between vertical momentum and arrival time has been proposed by Zholents [2] to produce a few picoseconds x-ray pulses in a storage ring. Both normal conducting [3,4] and superconducting (SC) cavities have been considered where the SC option has been chosen for CW operation. A set of cavities with 4MeV deflecting voltage and operating at 2.815 GHz, or the 8th harmonic of the fundamental RF frequency is required at APS. An additional set of cavities with identical parameters will be utilized to reverse the chirp and return the beam to its normal orbit.

Design, prototype and testing for the SC cavities have been carried out by a collaboration of ANL/JLab/LBNL and Tsinghua University. Efforts were primarily focused on the squashed elliptical shape optimization, single-cell cavity prototype, bench measurements and cold tests [1]. This effort was also extended into further design optimization of the single-cell unit for an integrated cryomodule design, suitable for SC infrastructure. The design challenging factors include the high current and the high deflecting gradient requirement, as well as the stringent APS impedance budget to ensure the coupled bunch stability at 200 mA beam current [5].

SINGLE-CELL VERSUS MULTI-CELL

In order to improve the active length of the deflecting cavity structure for a compact system, a natural extension of the single-cell cavity design consists of various multi-cell options. A two-cell cavity operating in the π-mode was explored, but unfortunately suffered from significant surface magnetic field enhancement at the cavity iris where B_{max}/E_{def} increased from 8.36 mT/(MV/m) for the single-cell cavity to 27.7 mT/(MV/m) for the two-cell cavity [6], as shown in Fig. 2. This enhancement is caused by the large iris radius R_{iris}/λ=0.235, which could not be reduced further due to the short-range wake effect from the beam. The large magnetic coupling through the iris of ~5.3% has been calculated by a double-chain model composed of TM11 and TE11 mode couplings [7]. Another challenge of the multi-cell design is the damping of the same pass-band modes (SPM) while not affecting the deflecting impedance [8]. One potential solution is the proposed 3-cell design operating in the π/2 (2π/3 in SRF nomenclature) mode, which uses an on-cell damper [9]. A possible improvement on the cell shape would further reduce the B_{max}/V_{def} value [10] in this proposal. Periodic damping structures [11] are possible, or the one recently proposed for the LHC crab cavity, where two cells operating at the 0-mode are separated sufficiently for dampers to be placed in between [12]. However, the single-cell cavity possesses many advantages over the multi-cell cavity, such as a minimum B_{max}/E_{def}, simplicity of chemical processing of cavity interior and damping all parasitic modes. As a result, there is considerable effort and promise in the performance capabilities of the single-cell as the preferred deflecting cavity geometry.

CAVITY PROTOTYPE AND COLD TESTS

Prototyping of a single-cell squashed elliptical cavity was started in 2007. A CAD model conforming to the Microwave Studio® (MWS)'s optimized design was used for the fabrication of the die. Half-cells were made using aluminium, copper and niobium material. The "dumbbell" measurement used a copper pair. They were step joined from iris to iris and clamped together by two racetrack shape flanges on equators. The trimming coefficient on the equator was measured to be 9.2±1.1 MHz/mm in 0-mode and 8.7±1.2 MHz/mm in π-mode respectively. MWS predicted this to be 8.4 MHz/mm and 7.6 MHz/mm respectively. The first single-cell prototype cavity was made with high-RRR Nb (right insert in Fig. 1). Its

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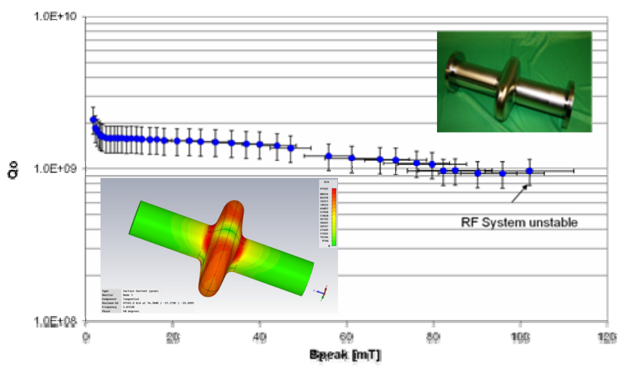

Figure 1: Maximum surface magnetic field (in TM110 0-mode) shown in the left insert (MWS graph) has reached 100mT in the first test. The limitation was due to the unstable VCO driven by large Lorentz force detuning.

vertical cold test at 2K in 2007 first achieved ~100mT surface magnetic field.

In 2008, a two-cell Nb cavity was made. The magnetic field enhancement operating in the π-mode can be shown on the top insert in Fig. 2 of Test #2. The 0-mode was measured in Test #1, the Q_0 was lower than the π-mode. Both results with less than 100mT B_{peak} were due to the RF power limitation from the fixed coupling.

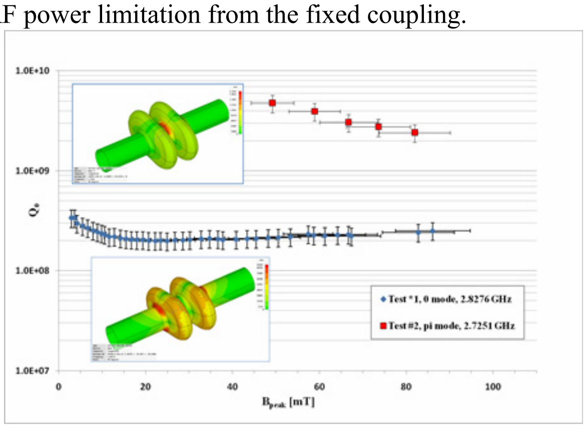

Figure 2: Surface magnetic fields measured in two RF tests in 2008. Test #1 (bottom) was operating in 0-mode. Test #2 (top) was measured in π-mode.

The first on-cell damper structure was made directly by machining the equators' slot to match a "saddle" adaptor in a 3-D contour. Three pieces were EB-welded both from the outside and inside through irises. A second adaptor joining the "saddle" and waveguide was made for the sequenced E-B welds. An alternative fabrication technique is to modify the cell's die for the opening slot, so the waveguide axis can be more accurately produced perpendicular to the cell's wall. The prototype shown in Fig. 3 was produced with the first method. It will be cold tested soon. If the waveguide axis is more than 1^{o} off from the racetrack short axis, a blank flange with stainless steel on the waveguide port will lower the Q_0 10 times more compared to the Q_0 achievable with a niobium blank flange. This accuracy is required for the on-cell damper

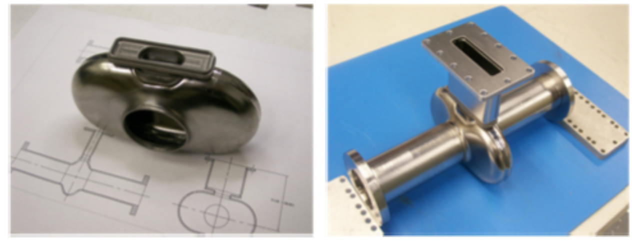

Figure 3: Second niobium prototype of on-cell waveguide coupling to cavity cell, left: after the first EB-weld, right: stack assembly before the final EB-weld.

on the squashed cavity, i.e. not damping the deflecting mode's energy. If this on-cell damping scheme works, overall longitudinal length of the structure could be reduced by 38%.

LORENTZ FORCE DETUNING

A large Lorentz force detuning (LFD) of ~0.6 Hz/mT^2 was measured in the first single-cell cavity test in 2007. A simulation effort has been carried out using ANSYS to confirm the experimental result and to reduce the response of cavity to the Lorentz force. The convergence of simulations was challenging due to the calculation of very small displacements and the EM fields on the rather complex 3D surface. In order to further confirm the LFD simulation results, the ANSYS eigen mode solver and separately calculated Slater method utilizing the field strengths and material displacements were compared and found to be consistent. A model with uniform shell thickness of ~3mm predicted an LFD of ~0.32 Hz/mT^2. On the other hand, a more accurate model conforming to an ultrasonic measurement where the shell thickness varied from 1 to 3 mm, and a free constraining boundary condition gave a value of ~0.47 Hz/mT^2, which was closer to the experimental value. To reduce the effect of LFD, a triangular stiffener attached on each long axis of the cavity wall was simulated. The LFD was reduced to a half of its previous value as shown in Fig. 4.

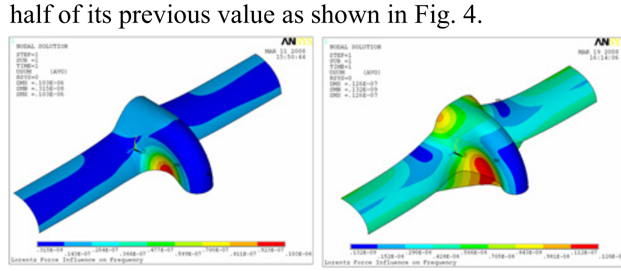

Figure 4: Cavity displacements due to the Lorentz forces as calculated by ANSYS, left: without stiffener, right: with triangle stiffeners in high deflection areas.

CAVITY IMPEDANCES

A copper cavity model with all waveguide dampers as shown in the picture insert on the top of Fig. 5 has been built to bench measure the impedance of parasitic modes. The straight waveguide on the right of the crab cell has been specifically designed for damping the strongly-coupled TM010 modes (LOM) and TE111 modes (SOM).

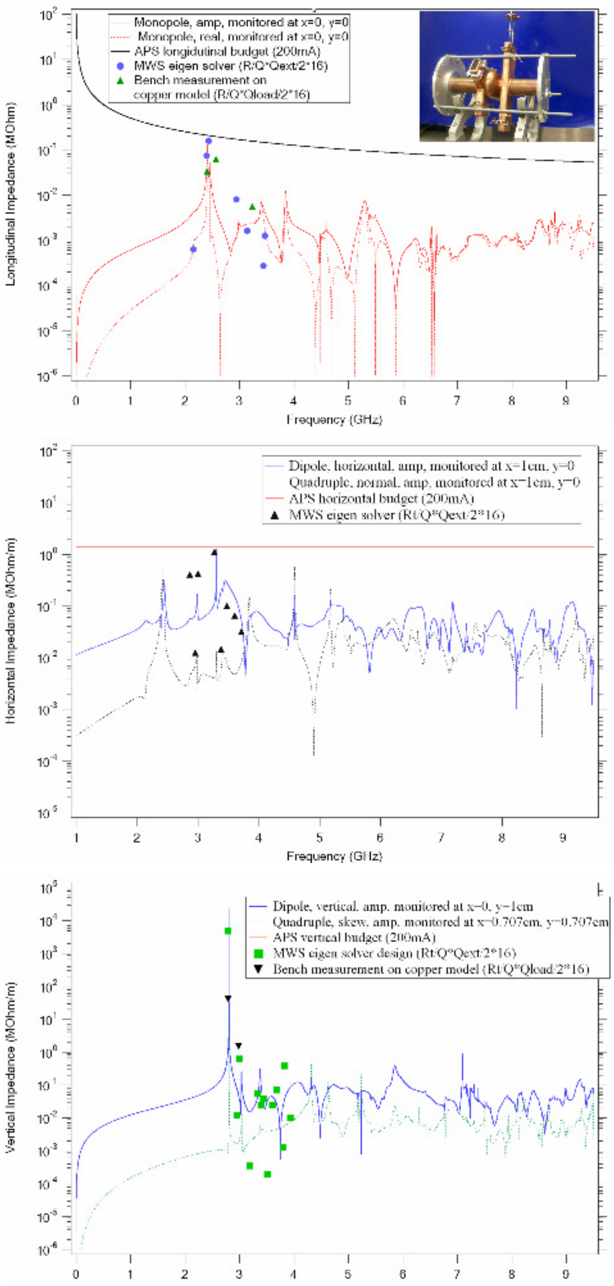

Figure 5: MAFIA calculated impedance versus impedance budgets in 3 directions for 16 single-cell damping units. Top: longitudinal; Middle: horizontal; Bottom: vertical.

A sliding short was used during testing to determine the optimum stub length [1]. The "Y" shape waveguide consisting of three damper ports is designed to damp the SOM and the HOM. A consequence of adding the damping waveguides to the single-cell structure was an increase in B_{max}/V_{def} from 157mT/MV to 196mT/MV.

The impedances of a single-cell cavity with damping structure have been calculated from the Fast Fourier Transform of the long-range wakes calculated with MAFIA using a new method for accurate extrapolation [13] and using a multi-beam excitation scheme to define the mode polarizations [14]. The total impedance for 16

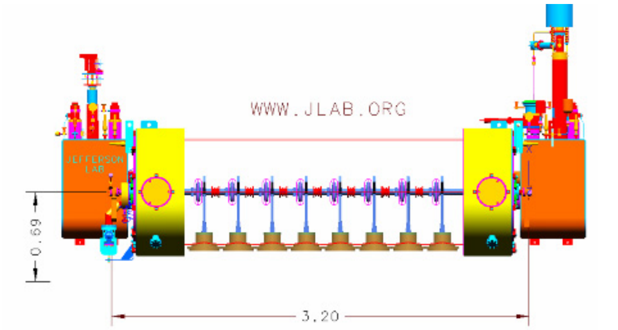

Figure 6: A conceptual of deflecting cryomodule containing 8 single-cell units is in 3.2m long and produces 4MV deflecting voltage.

single-cell cavities is 16 times the impedance calculated for a single-unit (see Fig. 5). Assuming a maximum peak surface magnetic field of 100mT, each single-cell cavity will generate 0.51 MV deflecting voltage or 8 MV deflecting voltage in total from two sets of 8 cavities.

The estimated total beam induced RF power into the cavity from longitudinal modes due to the APS hybrid mode bunch pattern (16mA/86mA) [4] would be 2.45 kW, where 51 W is damped in each waveguide load.

A preliminary cryomodule layout indicates that a JLab style cryomodule can host 8 cavities (see Fig. 6). One cryomodule is placed before the wiggler and another one is located after the wiggler. The total impedances of parasitic modes are under the budget for APS.

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