INTEGRATED SYSTEM MODELING ANALYSIS OF A MULTI-CELL DEFLECTING-MODE CAVITY IN CRYOGENIC OPERATION

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Abstract

Over the past decade, multi-cell deflecting (TM_{110}) mode cavities have been employed for experiments on six-dimensional phase-space beam manipulation [1 - 5] at the A0 Photo-Injector Lab (16 MeV) in Fermilab and their extended applications with vacuum cryomodules are currently scheduled at the Advanced Superconducting Test Accelerator (ASTA) user facility (> 50 MeV). Despite the successful test results, the cavity, however, demonstrated limited RF performance during liquid nitrogen (LN_2) ambient operation that was inferior to theoretic prediction. We thus fully inspected the cavity design with theoretical calculation (based on Panofsky-Wenzel theorem) combined with RF simulations. Also, we are extensively developing an integrated computational tool with comprehensive system analysis capacity to solve complex thermodynamics and mechanical stresses of a high-Q deflecting-mode cryomodule. We will benchmark simulation analysis result with experimental data from high power RF tests in Fermilab. Successfully developed modeling tool will be potentially used for prompt assessment on RF performance of vacuum-cryomodules.

INTRODUCTION

Deflecting-mode cavities have been used in a wide range of accelerator applications that include particle separation [1], temporal beam diagnostics [2], crab-crossing in colliders, x-ray pulse compression, longitudinal phase space characterization [3, 4] and phase space manipulation [5]. In particular, manipulation between the transverse and longitudinal phase space [6 – 8] and single shot diagnostics of longitudinal phase space (LPS) [3] have been actively investigated with multi-cell deflecting mode cavities. It is a very useful tool for controlling transverse and longitudinal emittances in 6-dimensional phase space. The kick strength of the fundamental deflecting mode (TM_{110}) is proportional to electric and magnetic field amplitudes, which are a function of ohmic-Q (Q_0) and transverse shunt impedance (R/Q). The power dissipated in a cavity is increased with an increase in the surface resistivity, $R_s = (\pi f \mu_0/\sigma)^{1/2}$, where σ is the conductivity. Also, phase-matched field distribution of multi-cell structures can improve field enhancement that possibly increases shunt impedance proportional to the number of cells. Therefore, in many cases cryogenic operation and multi-cell design are considered for deflecting mode cavities: multi-cell TESLA type cavities are made out of either normal conducting copper or superconducting niobium. As performance of the overmoded high-Q cavities are, however, highly sensitive to operational conditions, accurate control of cavity parameters is a nontrivial issue under cryo-cooling operation owing to the extremely narrow bandwidth of their resonance. A variety of perturbations such as mechanical vibration, microphonics, and thermal radiations could significantly change characteristic cavity impedance. In particular, thermal variation resulting from cryo-cooling and RF-loading is the major source of structural deformations that bring about frequency deviations, which will therefore need to be considered in the cavity design. (The heat source of beam-loading and higher-order-modes (HOMs)/ wakefields should also be included in the analysis when cavities operate in a CW or a high rep-rate mode of high intensity beam.) However, accurate simulation modeling of a realistic operational environment is still a challenging issue for the design of a stable cryogenic RF system. Although versatile simulation technology has noticeably advanced in plasma physics and mechanical engineering, system design analysis demands complicated computational steps of data processing, which may possibly lead to the loss of data accuracy and simulation efficiency. This paper discusses the cryogenic RF performance of the 5-cell deflecting mode cavity with numerical modeling analysis. It also presents up-to-date test simulation results of an integrated thermo-stress analysis modeling tool on the deflecting cavity vacuum-cryomodule.

SYSTEM DESCRIPTION

Figure 1 summarizes the simulation results of the TM_{110} mode cavity from two RF computational codes, CST and HFSS. The two sets of the cavity parameters agree reasonably well. In particular, coupling constants are each close to critical coupling ($\beta \sim 1$). (For the calculation, the copper conductivity was defined as $\sigma = 3.5 \times 10^8\ \Omega^{-1}m^{-1}$ at LN_2 temperature, ~ 80 K).

The two main parameters were examined with respect to klystron input driving powers of 50 kW and 80 kW, as a new, pulsed 80 kW, 3.9 GHz Varian model VA-908K2 klystron [9] has become available. Figure 2 shows that a 40 % loss of field uniformity drops the deflecting force, k, down to 1.1 from 1.4 and to 1.4 from 1.8 with 50 kW and 80 kW of klystron power, respectively. This corresponds to a ~ 27 % reduction of the deflecting force with 50 kW klystron power, whereas RF driving with 80 kW can improve it by 27 %. The influence of the coupling constant, β, on the deflecting force is relatively small; i.e. k = 1.4 (50 kW) and 1.8 (80 kW) at $\beta = 1 \rightarrow$ k = 1.35 (50 kW) and 1.7 (80 kW) at β = 0.5: only a 3.7 % and 5.8 % drop.

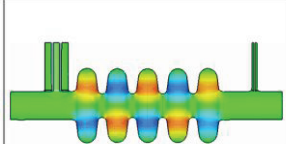
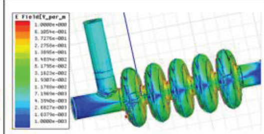
	CST	HFSS
Model		
f_L [GHz]	3.891	3.932
Q_0	41,769	38,700
Q_{ext}	45,059	37,760
Q_L	21,676	19,112
β	0.927	1.025
R/Q (/cell)	~ 23	~ 23

Figure 1: (a) Field distributions and simulation data, obtained from two EM simulation of a 5-cell deflecting mode cavity [10, 11].

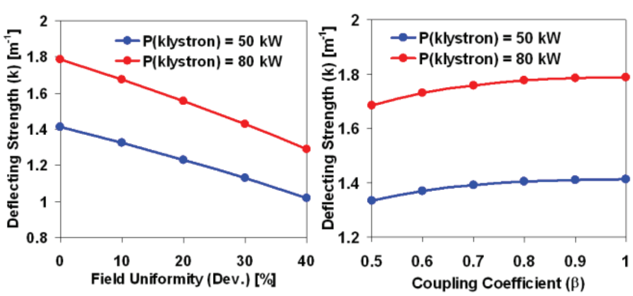


Figure 2: (a) Deflecting force versus (a) field non-uniformity (deviation) and (b) coupling coefficient (β), obtained from analytic calculation with eigenmode simulations. Beam energy is 40 MeV.

We conclude that the off-resonance coupling leads to a reduction in the kick strength because it more likely perturbs the field distribution, decreasing cell-to-cell field uniformity, rather than directly weakening the field strength. The accelerating potential vs. radial position and the deflecting force versus the field deviation. Note that the increasing rate of the deflecting field amplitude along the radial distance is noticeably reduced with loss of field uniformity, which is reflected in the deflecting force: kick strength drops down to 2.9 from 3.95 with 40 % non-uniformity (35.6 % reduction). Eventually, one can see that poorly coupled RF power, accompanying perturbation of the field distribution, possibly causes a 30 ~ 40 % deficiency of the deflecting strength.

SIMULATION MODELING

Figure 3 depicts the recently designed vacuum-cryomodule containing the 3.9 GHz 5-cell deflecting mode cavity that may be installed at the Fermilab ASTA user's facility. The system is designed with the vacuum insulator, which has good thermal insulation efficiency. Volumetric contraction and thermal fluctuation resulting from LN_2 cooling is no longer a critical factor since the vacuum insulator tank is an excellent heat reservoir for the LN_2 vessel, which linearly cools the ambient temperature down to 77 – 80 K and maintains it consistently. Instead, it is more critical to consider RF loading and beam loading for CW or high duty operation of high intensity or high power machines.

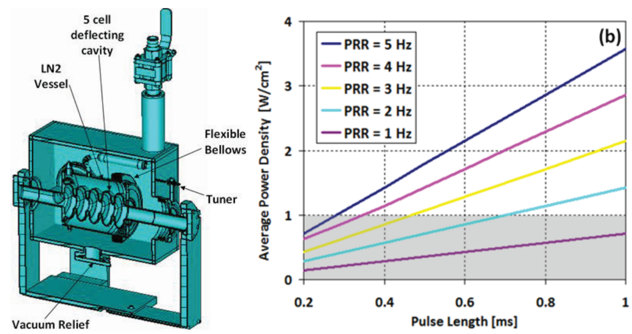


Figure 3: (a) Designed vacuum-cryostat with a 5 cell deflecting mode cavity (b) external cavity surfaces versus RF pulse length with respect to pulse repetition rate (PRR).

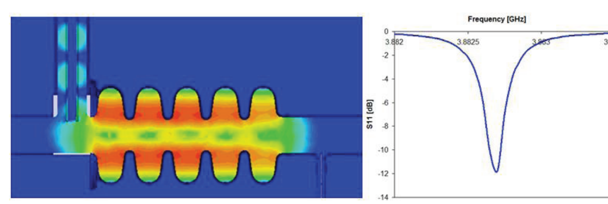


Figure 4: Frequency domain simulation result (a) power distribution of TM_{110} mode (b) S_{11} spectrum.

The frequency tuner is similar to the original design except that it is mounted on the vacuum tank with an additional flexible bellows. In this design, the amount of liquid nitrogen is controlled by the N_2 inlet and vent/relief and its level is monitored by the LN_2 level probe. The temperature of the LN_2 vessel remains constant by means of the vacuum insulation tank. However, even in the thermally insulated vacuum system energy of long pulse duration deposits a considerable amount of power on the cavity surfaces that can increase the ambient temperature so highly as to exceed the temperature threshold of bubble formation in the N_2 fluid. In Fig. 4, TM_{110} mode appears at f = 3.884 GHz with an insertion loss of –12 dB. The total Q (Q_L) of the operational mode is calculated to be ~ 36,000 and the inset of Fig. 4(a) shows the field distribution of the power fed into the cavity through the input coupler. The thermal losses are calculated with OFHC copper conductivity ($\sigma = 3.5 \times 10^8$ S/m) at 80 K and the calculated data are exported to the thermal stationary solver. Figure 5 is temperature increase graph with a 1 ms/5 Hz pulse of 80 kW klystron power. Figure 6 depicts a geometrical displacement of deformed structure, calculated from transferred thermal distribution data. Under the same pulse condition (1 ms/5 Hz), the

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simulation results in maximum Von Mises stress of 0.005971 GPa, leading to an ~ 4.36 μm maximum displacement. The irises undergo the highest pressure, while maximum deformations appear at the equators.

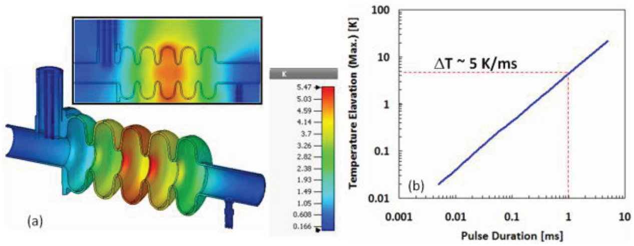

Figure 5: (a) temperature elevation versus pulse duration with 5 Hz PRR (b) maximum dimensional deformation versus pulse duration graph with 5 Hz PRR.

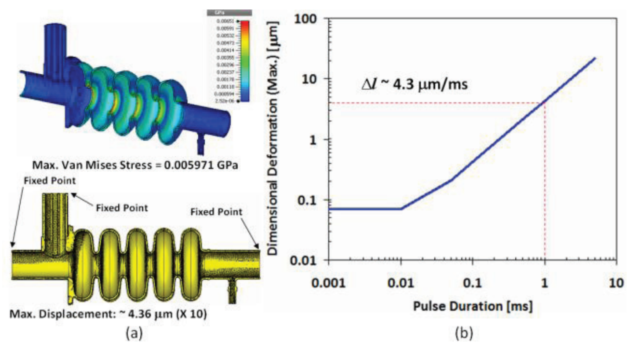

Figure 6: Mechanical structural simulation results with transferred thermal loss data of Fig. 5 (a) 3D plot of Von Mises stress (top) and geometrical displacement (structural deformation, bottom), and (b) maximum dimensional deformation versus pulse duration graph.

The dimensional deformation versus pulse duration (with 5 Hz PRR, Fig. 6) graph is obtained from the structural modeling analysis. Note that pulse widths below 10 μs do not cause a detectable change of dimensional deformation (max.) on cavity geometry. Deformation steeply increases with pulse width above 100 μs, which causes 0.2 ~ 4.3 μm displacement (max.) with up to 1 ms. The displacement of thermal energy deposition causes an 7.3 MHz frequency shift on the TM_{110} mode, which is beyond the FWHM (full-width-half-maximum) bandwidth of the input signal. Eventually, we calculated a frequency deviation with respect to pulse durations under the same PRR condition. The summarized simulation results show that the designed system has a sensitivity of 1.7 MHz/μm/ms or 1.46 MHz/K/ms. The correction resulting from RF-loading should thus be included in cavity design for enabling optimal operation and accurate control of the vacuum-cryomodule.

CONCLUSION

A normal conducting multi-cell deflecting mode cavity has been used for various beam control applications in an LN_2-vessel at the Fermilab A0 PI and currently it is planned to accommodate vacuum-cryomodules of either normal conducting or superconducting deflecting mode cavities in the ASTA beam line for higher energy beam tests. Despite successful test results of the previous experiments on 6D phase-space manipulation, the 5-cell cavity demonstrated limited performance. Theoretical and numerical investigation of the LN_2-ambient operational parameters showed that a reduction of kick strength could be ascribed to an improper impedance matching condition of the input coupler and non-uniform cell-to-cell field distribution. Volumetric change of the cavity dimensions resulting from LN_2-cooling should be embedded in the design process to determine the correct operating frequency. The drafted 5-cell vacuum-cryomodule design for the ASTA beamline application was studied with the batched multiple simulation process, including RF, thermal, and mechanical solvers. The combined simulation results showed that thermal fluctuation arising from excessive cavity RF-loading can cause severe structural deformation and frequency deviation with long pulse length, high repetition rate operation. Also, the analytic correction will need to be considered in the high-Q cavity design. Currently, more systematic optimization of the sensitivity modeling analysis on the deflecting mode vacuum-cryomodule is under consideration in comparison with experimental data.

REFERENCES

[1] D. A. Edwards, Editor, Fermilab TM-2060, October 1998.

[2] C. Hovater, et. al., LINAC96, Geneva, Switzerland, 77 (1996).

[3] D. Alesini, "RF deflector-based sub-ps beam diagnostics: application to FELs and advanced accelerators", in Physics and Applications of High Brightness Electron Beams (World Scientific, 2006) Erice, Sicily, 2005; see also J. T. Moody, P. Musumeci, M. S. Gutierrez, J. B. Rosenzweig, and C. M. Scoby, Phys. Rev. ST Accel. Beams 12, 070704 (2009).

[4] R. Akre, L. Bentson, P. Emma, and P. Krejcik, "A Transverse RF deflecting structure for bunch length and phase space diagnostics," Proc. 2001 Particle Accelerator Conf., Chicago, June 2001, (2001) 2353.

[5] P. Piot, D. R. Douglas, and G. A. Krafft, Phys. Rev. ST Accel. Beams 6 030702 (2003).

[6] Y. Orlov, C. M. O'Neill, J. J. Welch, and R. Sieman, Proceeding of 1991 Particle accelerator Conferences, San Francisco CA, 2838 (1991).

[7] M. Cornacchia and P. Emma, Phys. Rev. ST Accel. Beams 5, 084001 (2002).

[8] P. Emma, Z. Huang, K.-J. Kim, and P. Piot, Phys. Rev. ST Accel. Beams 9, 100702 (2006).

[9] CPI Inc., http://www.cpii.com

[10] T. W. Koeth, PhD Thesis of Northern Illinois University, 2009.

[11] T. W. Koeth, PAC2007 Albuquerque, 2007.

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