SIMULATION OF MECHANICAL OSCILLATIONS IN PIP-II CRYOMODULE USING ACE3P*

Liling Xiao, Oleksiy Kononenko, Cho-Kuen Ng
SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

Abstract

The linac in PIP-II project at Fermilab consists of different sections of superconducting RF (SRF) cavities that can accelerate the proton beams to 800 MeV. At the end of the linac is a section containing four high β (β = 0.92) cavity cryomodules (CM) operating at 650 MHz, with each one having six SRF cavities. The mechanical modes in a single high beta 650 MHz dressed cavity have been calculated previously. In this paper, the parallel code suite ACE3P is used to simulate the mechanical modes in a string of the high beta 650 MHz multi cavities. The effects of multi cavities on the mechanical mode frequencies and any possible coupling between cavities will be investigated.

INTRODUCTION

Proton Improvement Plan-II (PIP-II) will provide powerful, high-intensity proton beams to the neutrino program at Fermilab. The central construction of PIP-II is an 800 MeV superconducting linac (SCL) injecting into the existing Booster [1]. SCL consists of five types of SRF cavities required for the beam acceleration from low velocity to speed of light [2]. The main parameters of SCL cavities are listed in Table 1.

Table 1: Main Parameters of SCL Cavities

Cavity	β	F (MHz)	E (MV)	CM	Cavity/CM
HWR	0.11	162.5	2.1-11	1	8
SSR1	0.22	325	11-38	2	8
SSR2	0.47	325	38-177	7	5
LB650	0.61	650	177-480	10	3
HB650	0.92	650	480-800	4	6

PIP-II SCL SRF cavities will work in pulsed mode but are compatible with future CW operation. Low beam current with a peak current of 2 mA in combination with high Q_0 results in narrow cavity bandwidth of ~ 60 Hz, and thus the RF field stability is very sensitive to Lorentz Force Detuning (LFD) and microphonics. Therefore, simulating mechanical modes and studying cavity response to various external vibrations for each type of the cavities are essential.

Previous mechanic calculations have been carried out using COMSOL to determine LFD, df/dP (the sensitivity of the cavity resonant frequency to He bath pressure), and the mechanical modes in a single dressed cavity for each type of SCL cavities [3]. The mechanical mode frequencies in a single cavity depend on the boundary conditions imposed on the cavity, which may differ from those in a CM.

The parallel code suite ACE3P developed at SLAC has multi-physics capabilities in integrated electromagnetic, thermal and mechanical simulation [4]. Implemented on massively parallel computers for increased memory, ACE3P makes the mechanical mode simulations for a string of SRF cavities possible. In this paper, the mechanical modes in the high beta 650 MHz CM, as shown in Figure 1, are evaluated using ACE3P.

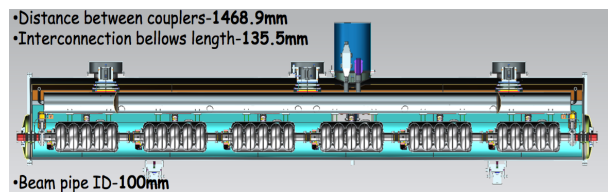

Figure 1: PIP-II high beta 650 MHz CM concept design.

A SINGLE DRESSED CAVITY

FNAL has finished the PIP-II high beta 650 MHz cavity mechanical design as shown in Figure 2. The original blade tuner design has been replaced by a scissor side tuner, which can achieve low df/dP, and be better tunable and less expensive [3,5,6].

First the mechanical modes in a single dressed cavity with and without tuner are analyzed in the following.

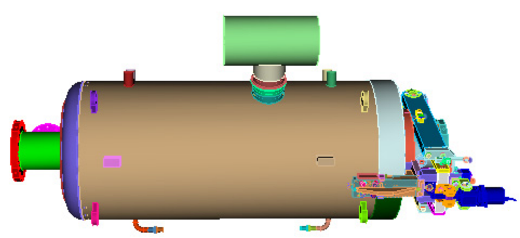

Figure 2: PIP-II high beta 650 MHz dressed cavity

Dressed Cavity without Tuner

A half of the geometry, as shown in Figure 3, is meshed with curved quadratic elements for the mechanical mode simulations. The cavity and stiffening rings are made of Nb (green), the two end transition plates as well as the beampipe and power coupler flanges NbTi (yellow), and the support tabs on the Helium tank stainless steel (blue), respectively, and the Helium tank is made of Ti (grey).

* Work supported by the US DOE under contract DE-AC02-76SF00515

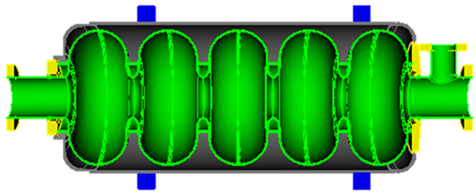

Figure 3: A half of PIP-II high beta 650 MHz dressed cavity without tuner.

The material properties used in the simulations are listed in Table 2. The boundary conditions assume that the four support tabs are fixed in all directions as well as the symmetrical plane in the normal direction. The rest of the boundaries are free to deform. The first ten mechanical mode frequencies calculated using ACE3P are listed in Table 3 in which the longitudinal modes are marked with red. Because one half of the structure is simulated, only the transverse mechanical modes in the horizontal direction are solved.

Table 2: Material Properties at 2K

Materials	Young's Module (GPa)	Poisson's Ratio	Density (N/m)
Nb	118	0.38	8700
NbTi	68	0.33	5700
Ti	117	0.37	4540
SS	193	0.29	8000

Table 3: The mechanical mode frequencies in a single PIP-II high beta 650 MHz dressed cavity without tuner.

Index	F (Hz)	Index	F (Hz)
1	44	6	189
2	**58**	7	215
3	114	8	258
4	124	**9**	**269**
5	**166**	10	333

Dressed Cavity with Tuner

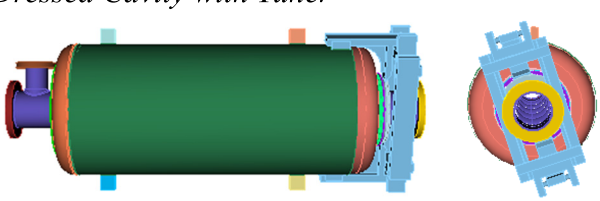

Figure 4: A full PIP-II high beta 650 MHz dressed cavity with tuner.

The side tuner can push or pull the cavity through the end transition plate to compensate the cavity detuning due to LFD or the cavity mechanical modes excitation. A simplified scissor tuner is built for the model, and the resulting single dressed cavity with tuner is shown in Figure 4. Without symmetry, the full geometry model is simulated and the mechanical mode frequencies are listed in Table 4 in which the longitudinal modes are marked with red. In these simulations, the tuner is fixed against only axial motion.

Table 4: The mechanical mode frequencies in a PIP-II high beta 650 MHz dressed cavity with tuner.

Index	F (Hz)	Index	F (Hz)
1	50	11	218
2	54	12	219
3	107	13	259
4	**111**	14	262
5	123	15	267
6	128	16	270
7	152	17	279
8	201	18	281
9	**207**	**19**	**289**
10	214	20	326

The longitudinal mechanical modes have more contributions to the cavity RF detuning than the transverse modes. The first three longitudinal mechanical modes in the cavity with and without tuner are presented in Figure 5. With the introduction of tuner in the model, the cavity mechanical mode frequencies are quite different. The first longitudinal mechanical mode frequency is above 100 Hz in a single PIP-II high beta 650 MHz dressed cavity with tuner, compared with 58 Hz without.

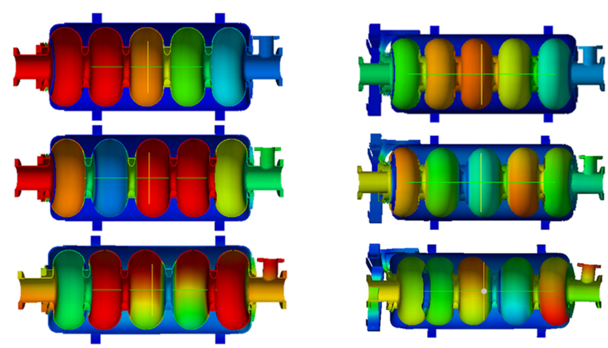

Figure 5: The lowest three longitudinal mechanic mode displacement profiles without (left) and with (right) tuner.

A STRING OF MULTI CAVITIES

The mechanical mode frequencies in a single cavity depend on the boundary conditions imposed on the cavity, which may differ from those in a CM. Therefore, the mechanical mode frequencies in a string of multi cavities need to be investigated.

The mechanical modes in a string of two and three cavities, as shown in Figure 6 and 7, are simulated. Their mode frequencies below 300 Hz as well as the ones in a single cavity are plotted in Figure 8. There are some extra modes in a string of the multi cavities, which are not supported in a single cavity.

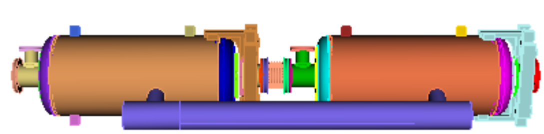

Figure 6: A string of two PIP-II high beta 650 MHz cavities.

ISBN 978-3-95450-169-4

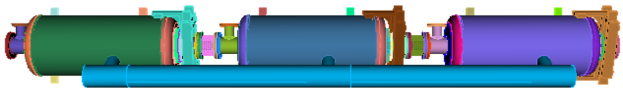

Figure 7: A string of three PIP-II high beta 650 MHz cavities.

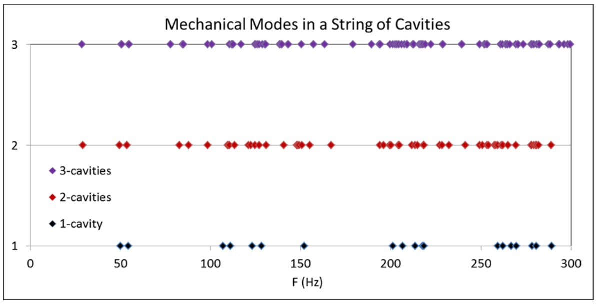

Figure 8: The mechanical mode frequencies in a string of PIP-II high beta 650 MHz multi cavities.

For a string of three cavities, three million quadratic elements are generated for the mesh used for simulation. With second order basis functions for the finite elements, one mechanical mode can be solved within a few minutes on NERSC Cori using 240 processors.

In Figure 8, it shows that there are some extra modes in a string of the multi cavities which are not supported in a single cavity. Some of them are localized at the He gas return (HGR) pipe, or the bellows between cavities. In addition, there are cavity modes coupled to HGR, and thus there are significant transverse displacement components in the longitudinal mechanical modes in a string of the multi-cavities.

The first longitudinal modes in a single cavity, a string of the two- and three-cavities are shown in Figure 9.

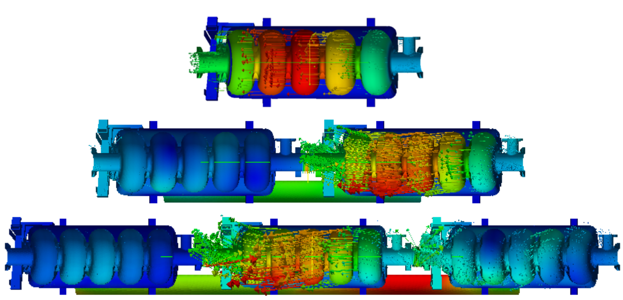

Figure 9: The first longitudinal mechanical mode displacement maps in a single cavity (up, F=111.1 Hz), a string of the two cavities (middle, F=109.5 Hz), and a string of three cavities (down, F=111.7 Hz).

FUTURE WORK

The mechanical oscillations in a string of PIP-II high beta 650 MHz multi cavities have been simulated. The mode frequencies differ from those in a single cavity. The longitudinal modes in a string of the multi-cavities have transverse displacement components due to HGR pipe. And the modes in one cavity can couple to those in another cavity. Therefore, if one cavity is vibrated by an external force, the other cavities might be detuned due to the mechanical mode excitations.

We will further perform the mechanical mode simulation in the whole CM. When the Piezo tuner actuator moves in one cavity, the mechanical modes in the cavity might be excited, and thus cause the cavity detuned. In addition, the excitation of one cavity mechanical mode might affect another cavity detuning. We plan to study the cavity response to various external sources including static Piezo load and Piezo actuator motion, similar to the investigation for LCLS-II 1.3 GHz cavity [7].

ACKNOWLEDGMENT

The authors want to thank T. Nicol of FNAL for providing the PIP-II high beta 650 MHz mechanical CAD model and V. Yakovlev for useful discussions. The research used resources of the National Energy Research Scientific Computing Center, which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

REFERENCES

[1] https://pip2.fnal.gov/

[2] Paul Derwent, "PIP-II R & D Program", DOE Independent Project Review of PIP-II, June 16, 2015.

[3] T. Khabiboulline, "The Cavity EM and Mechanical Design Issues and Status", PIP-II Meeting, Sept. 16, 2014.

[4] https://confluence.slac.stanford.edu/display/AdvComp/Materials+for+CW14

[5] S. Barbanotti *et al.,* "Status of the Mechanical Design of the 650 MHz Cavities for Project X", PAC11, March 28 to April 1, 2011, New York, NY, USA.

[6] I. Gonin *et al.,* "Update of the Mechanical Design of the 650 MHz Beta=0.9 Cavities for Project X", IPAC13, May 12 to 17, 2013, Shanghai, China.

[7] O. Kononenko *et al.,* "Electro-Mechanical Modeling of the LCLS-II Superconducting Cavities", presented at LINAC'16, East Lansing, MI, USA, Sept. 2016, MOP106006.