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SIMULATIONS OF MECHANICAL MODES IN PIP-II HIGH BETA 650 MHZ CRYOMODULE USING ACE3P

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Abstract

The linac in Proton Improvement Plan-II (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, each one having six SRF cavities. The calculations of mechanical modes in a single high beta 650 MHz dressed cavity have been carried out using COMSOL. As the mechanical modes in a CM differ from that in a single cavity, in this paper, the parallel code suite ACE3P is used to simulate the mechanical modes in PIP-II high beta 650 MHz 6-cavity CM. 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 PIP-II 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 on pulsed but are compatible with future CW operation. Low beam current with a peak current of 2 mA combination high Q_0 results narrow cavity bandwidth of ~60 Hz, and thus the RF field stability is very sensitive to Lorentz Force Detuning (LFD) and microphonics. Simulating mechanical modes and studying cavity response to various external vibrations for each type of the cavities are essential.

Mechanic calculations have been carried out to determine LFD, df/dP (the sensitivity of the cavity mechanical mode resonant frequency to Helium bath pressure), and the mechanical modes in a single dressed cavity for each type of SCL cavities [3]. The mechanical modes in a single cavity depend on the boundary conditions of the cavity, which differ from that in a CM. Therefore, the mechanical modes in a CM need to be investigated through high performance computing (HPC).

SLAC has developed the parallel electromagnetics simulation code suite **ACE3P** (**A**dvanced **C**omputational **E**lectromagnetics **3D P**arallel), consisting of 6 modules as described in Figure 1. ACE3P integrated EM, thermal and mechanical multi-physics characteristics have been applied extensively for accelerator design and optimization [4].

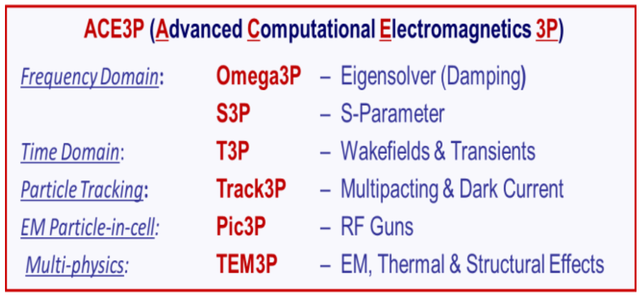

Figure 1: ACE3P application modules.

ACE3P codes are developed based on the high-order finite-element method. Geometries of complex structures can be represented with high fidelity through conformal grids, and high solution accuracies can be obtained using high-order basis functions in finite elements. With HPC resources for increased memory, ACE3P can solve large and complex problems such as accelerator cryomodule.

TEM3P, a mechanical harmonic analysis solver of ACE3P, is used to simulate the mechanical modes in a PIP-II high beta 650 MHz CM as shown in Figure 2.

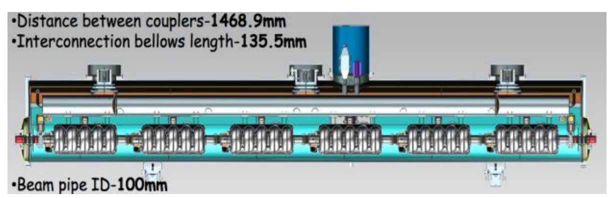

Figure 2: PIP-II high beta 650 MHz CM concept design.

A SINGLE DRESSED CAVITY

We will start to analyze the mechanical modes in a PIP-II high beta 650 MHz single dressed cavity with and without tuner in this section.

FNAL has finished PIP-II high beta 650 MHz cavity mechanical design as shown in Figure 3. Original blade

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tuner design has been replaced by end scissor tuner, which can achieve low df/dP, and is tunable and less expensive [3].

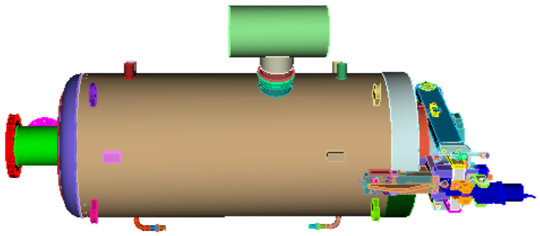

Figure 3: PIP-II high beta 650 MHz dressed cavity CAD model.

Dressed Cavity without Tuner

Without tuner, a half of the geometry, as shown in Figure 4, can be used for mechanical simulations. A half of the geometry is meshed using quadratic elements with curved surfaces. The cavity and stiffening rings are made of Nb (green). The Helium tank is made of Ti (grey). The two end transition plates as well as the flanges at the beampipes and power coupler are made of NbTi (yellow). The support tabs on the Helium tank are made of stainless steel (blue).

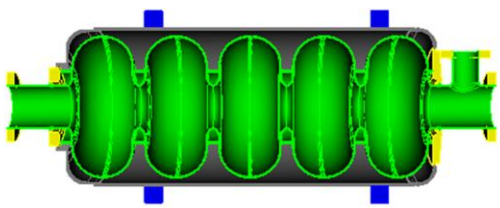

Figure 4: A half of PIP-II high beta 650 MHz dressed cavity without tuner.

The material properties used in the simulations are listed in Table 2.

Table 2: Material properties.

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

The four support tabs representing the support arms for the dressed cavity at all directions as well as the symmetrical plane at the normal direction are assumed to be fixed, and the remaining boundaries are allowed to deform. The first ten mechanical mode frequencies are listed in Table 3 in which longitudinal modes are marked in red. Due to modeling a half of the structure, only the transverse mechanical modes at horizontal plane along the power coupler are solved.

Table 3: The mechanical mode frequencies in a half of 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

In Ref. [3], the lowest two longitudinal mode frequencies are 60Hz and 174Hz, which are higher than those in Table 3. The main reason that causes the difference is that there are no constrained support tabs. Instead there are two blocks attached to the tank fixing the tuner as shown in Figure 5.

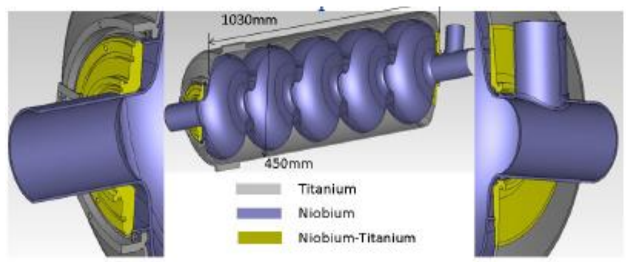

Figure 5: A half of PIP-II high beta 650 MHz dressed cavity model in Ref.[3]. (Courtesy by T. Khabiboulline)

Dressed Cavity with Tuner

The model difference between Figures 4 and 5 can affect the results. In this section we will add the stainless steel end tuner into the model. The end tuner can push or pull the cavity through the end transition plate to compensate the cavity detuning due to cavity mechanical mode excitations. A simpler end scissor tuner is built, and a single dressed cavity with tuner is presented in Figure 6.

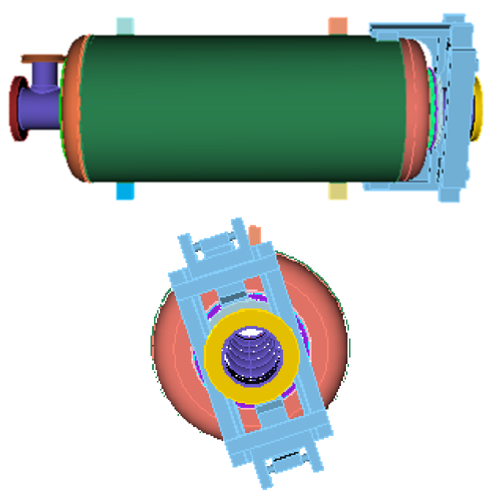

Figure 6: PIP-II high beta 650 MHz dressed cavity with tuner.

Without symmetry, the full geometry of PIP-II high beta 650 MHz dressed cavity model is simulated. Except the four support tabs fixed at all directions, the tuner is fixed against only axial motion, and the rest free. The lowest 10 mechanical mode frequencies are listed in Table 4 in which the longitudinal modes are marked in red.

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	6	128
2	54	7	152
3	107	8	201
4	**111**	**9**	**207**
5	123	10	214

The longitudinal mechanical modes contribute more to the cavity RF detuning than the transverse modes. The lower the frequency is, the more harmful the mode would be. With or without tuner, the cavity mechanical mode frequencies are quite different. It is good to learn that in this more realistic model with tuner the lowest longitudinal mode frequency is increased from 58Hz to 111Hz.

The first two longitudinal mechanical modes in the cavity with and without tuner are presented in Figure 7.

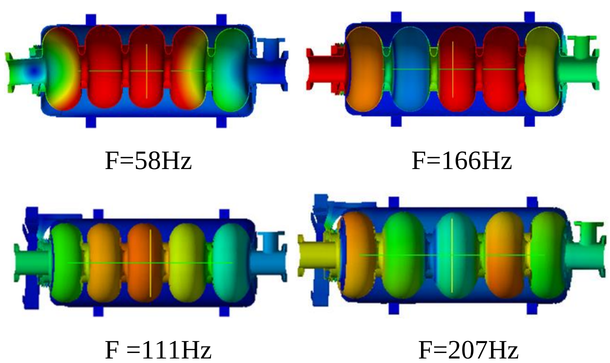

Figure 7: The lowest two longitudinal mechanical mode displacement profiles without (up) and with (down) tuner at the horizontal plane.

Fully Dressed Cavity

Because the geometry features can greatly affect the mechanical mode results, a fully dressed cavity including helium gas return pipe (HGR) and the bellows between cavities, as shown in Figure 8, is simulated. The bellows and HGR are both made of stainless steel.

The same boundary conditions are set as those in the previous sections. The modes below 200 Hz are listed in Table 5. Adding the HGR and bellows does not affect the cavity lowest longitudinal mode, but creates many extra modes located in the HGR and bellows compared with a simple dressed cavity. The cavity modes are marked in bold. The lowest longitudinal mode in the fully dressed cavity is presented in Figure 9.

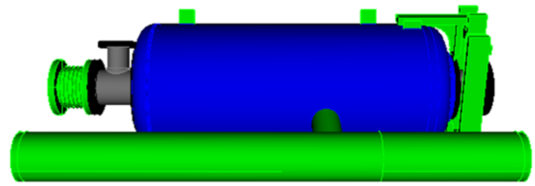

Figure 8: PIP-II high beta 650 MHz fully dressed cavity including the bellows between cavities and helium gas return pipe.

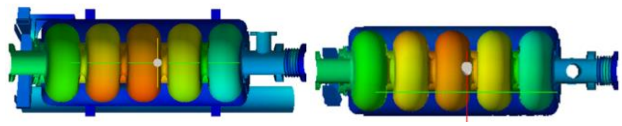

Figure 9: The lowest longitudinal mechanical mode displacement profiles at xplane (left) and yplane (right).

Table 5: The mechanical mode frequencies in a PIP-II high beta 650 MHz fully dressed cavity.

Mode Index	F (Hz)	Notes	Mode Index	F (Hz)	Notes
1	16.23	HGR	**12**	**118.15**	**Cavity-Ty**
2	23.44	HGR	**13**	**123.15**	**Cavity-Tx**
3	23.92	Bellows	14	127.53	Bellows
4	23.99	Bellows	**15**	**129.98**	**Cavity-Ty**
5	33.38	HGR	16	143.09	Bellows
6	**49.87**	**Cavity-Tx**	17	143.35	Bellows
7	**54.06**	**Cavity-Ty**	**18**	**151.32**	**Cavity-Tx**
8	80.54	Bellows	19	161.13	Bellows
9	87.03	Tank	20	163.84	HGR
10	**110.57**	**Cavity-Ty**	**21**	**197.47**	**Cavity-Ty**
11	111.28	Cavity-L	**22**	**200.90**	**Cavity-Tx**

A STRING OF TWO CAVITIES

The boundary conditions at the two ends of a single dressed cavity and a dressed cavity in a CM are different, and thus their mechanical modes frequencies are different. Therefore, it is necessary to perform the mechanical mode simulations in a CM.

The six cavities in PIP-II high beta 650 MHz cryomodule are identical. It will be efficient to use one cavity mesh we have generated to create a CM mesh using a mesh merging method.

A new Mesh Merging Tool (MMT) has been developed in ACE3P and applied to generate meshes for many large scale models. The following describes the steps of generating mesh by using MMT:

1) Divide the whole model into several small pieces.
2) Generate mesh for each piece using CUBIT mesh generation tool [8], but keep merging intersection surface meshes identical.

3) Generate a whole mesh through MMT
    a. Merge different meshes of the pieces;
    b. Add boundary conditions;
    c. Validate merged mesh.

MMT not only improves the performance for mesh generation, eases memory limitation, but also improves mesh quality by targeting small complicated features locally. MMT has been used in this application to mesh a string of two cavities as shown in Figure 10.

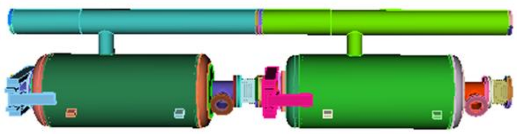

Figure 10: A string of PIP-II high beta 650 MHz fully dressed two cavities.

The meshes on the two surfaces to be merged must be identical. Therefore, the mesh for one cavity is generated with special care using CUBIT. The mesh copy function in CUBIT is used that allows copying one surface mesh to another. In order to prevent the mesh entities rotated during the mesh copy, the end surface at the beampipe flange and HGR is split into 4 and 3 surfaces. Then each separated surface at one end of the model is meshed and copied onto its mirror surface at the other end. The meshes at the two end surfaces are identical that can be merged later as shown in Figure 11. There are 722 K elements in a single model mesh, and the simulation results are converged with this mesh quality.

When merging two identical cavities meshes, the two interface meshes are merged into one. A string of two cavities mesh has 1429 K elements after merging two identical cavity meshes. All mesh entities IDs are rearranged as well as the boundary IDs.

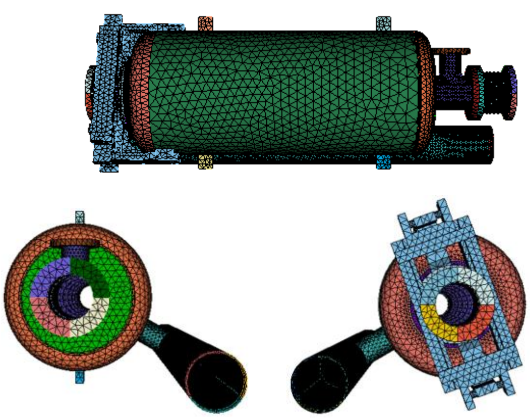

Figure 11: PIP-II high beta 650 MHz fully dressed cavity mesh with identical mesh entities at the two end surfaces.

Assuming the four support tabs on each cavity are fixed at all directions as before, and the tuners of each cavity are constrained at z-direction, the lowest 10 modes are listed in the Table 6.

Meanwhile, the two-cavity model is meshed directly having 1512 K elements, which has similar mesh quality as the 722 K elements single cavity mesh. The results are also listed in Table 6 for comparison. The results obtained from the two meshes agree very well.

Table 6: The mechanical mode frequencies in a string of PIP-II high beta 650 MHz fully dressed two cavities.

Mode Index	Mesh 2-Cavity 1512 K elements F (Hz)	Merge 2 Cavities 1429 K elements F (Hz)
1	23.91	23.92
2	23.98	23.99
3	26.39	26.39
4	49.17	49.15
5	49.81	49.78
6	51.14	51.12
7	53.83	53.80
8	55.06	55.05
9	55.70	55.68
10	79.46	79.49

A CRYOMODULE

MMT also is used to create mesh for PIP-II high beta 650 MHz CM model. Figure 12 shows CM mesh, which has 4.3M mesh elements. The problem is solved using 10 nodes, 320 CPUs on Cori at National Energy Research Scientific Commuting Center (NERSC) at Lawrence Berkley National Lab. It takes less than 10 minutes per mode calculation.

Because of the coupling between two cavities, the cavity mode frequencies will spread, and there are some modes localized between cavities. In addition, the lowest local modes between 16 Hz to 23 Hz in HGR of a single dressed cavity disappear. The mechanical mode frequencies in a CM and a single cavity are plotted in Figure 13. The lowest longitudinal cavity band modes in 650 MHz CM is presented in Figure 14.

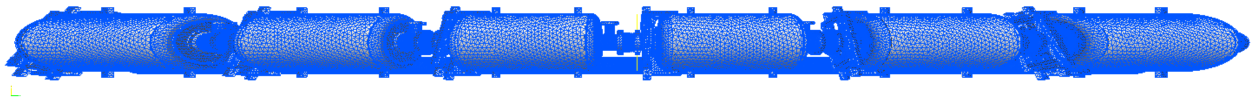

Figure 12: PIP-II high beta 650 MHz CM mesh.

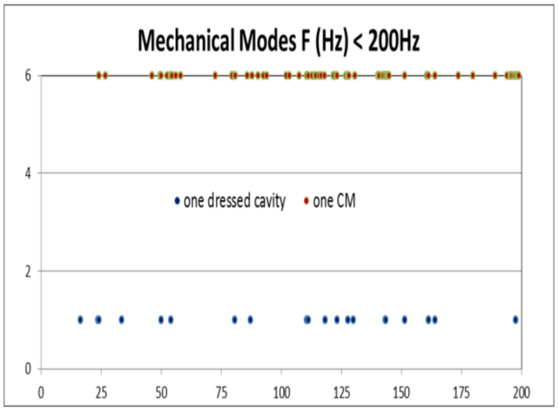

Figure 13: The modes in a PIPI-II high beta 650 MHz CM and a single cavity.

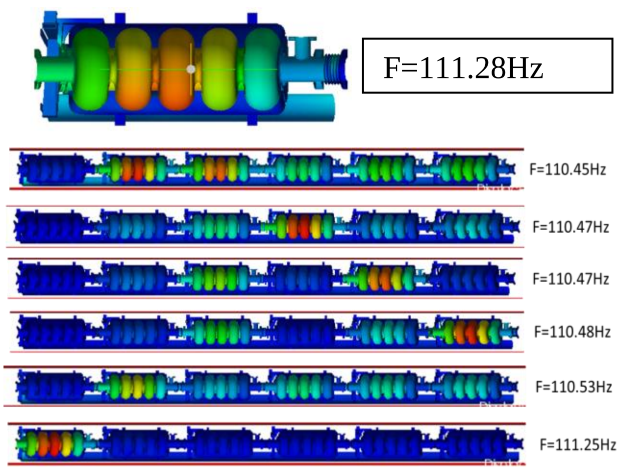

Figure 14: The lowest longitudinal cavity band modes displacement profiles at xplane in a single cavity (up) and in a CM (down).

SUMMARY

The mechanical oscillations in a PIP-II high beta 650 MHz 6-cavity CM have been simulated using the mechanical analysis solver TEM3P in the finite element parallel EM code suite ACE3P. The model we simulated might differ from the real one, but it can help understand the mechanical performance through the simulations. The mode frequencies in a CM differ from those in a single cavity. The longitudinal modes have transverse displacement components due to HGR pipes and tuner which destroy the geometry symmetry.

A mechanical mode in one cavity can couple to those in other cavities. If one cavity is vibrated by external force, the other cavities might be detuned due to the mechanical mode excitation. In addition, when one Piezo tuner actuator moves, the cavities will be deformed, and this will detune the other cavities. We plan to study the cavity response to various external sources in PIP-II high beta 650 MHz CM, such as static Piezo load and Piezo actuator motion as have been done for LCLS-II 1.3 GHz cavity [9].

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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] O. Konoenko, “A Massively Parallel Solver for Mechanical Harmonic Analysis of Accelerator Cavities”, SLAC-PUB-16229
[6] S. Barbanotti, et al., “Status of the Mechanical Design of the 650 MHz Cavities for Project X”, PAC11, March 28 – April 1, 2011, New York, NY, USA
[7] 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.
[8] https://cubit.sandia.gov/
[9] O. Konoenko, et al., “Electro-Mechanical Modeling of the LCLS-II Superconducting Cavities“, LINAC16, Sept. 25 to 30, East Lansing, MI.