PHASE AND AMPLITUDE TUNING ALGORITHMS FOR THE FRIB SUPERCONDUCTING CAVITIES *

Yan Zhang#, Paul Chu, Zhengqi He
FRIB, Michigan State University, East Lansing, MI 48824, USA

Abstract

FRIB driver linac will deliver all heavy ion beams up to uranium for beam energy above 200 MeV/u and maximum beam power on fragment target 400 kW for nuclear physics researches. Phase and amplitude tuning of all the FRIB superconducting cavities – 332 of them in the linac, are important to low power beam commissioning as well as high power operations. Because of relatively low beam energy and high acceleration gradient, the particle velocity changes significantly in the cavity RF gaps and the beam bunch structure cannot be preserved perfectly in the further downstream beam diagnostics, beam longitudinal tuning algorithms are studied for different types of FRIB cavities and for various beam energies, which include acceleration cavities as well as re-buncher cavities.

INTRODUCTION

The FRIB, Facility for Rare Isotope Beams, is currently under construction on the campus of MSU, Michigan State University. The project is funded by the US Department of Energy Office of Science, MSU, and the State of Michigan. The total budget of the project is about 730 million dollars, and it will be completed in 2022 [1].

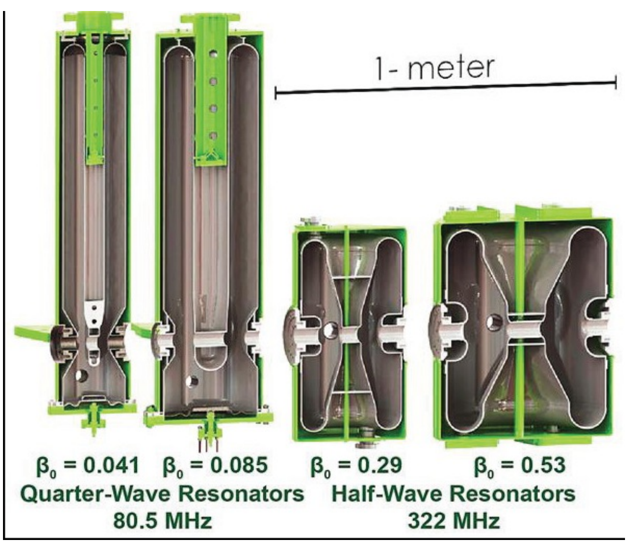

Figure 1: The FRIB cavities: beta 0.041 and 0.085 QWRs, 80.5 MHz; beta 0.29 and 0.53 HWRs, 322 MHz.

The FRIB driver linac is a state-of-the-art high power CW linac, and it includes 4 different types of SRF cavities as shown in Figure 1. Two types of quarter wave resonators (QWR) accelerate beams from 0.5 to 20 MeV/u, and then two types of half wave resonators (HWR) accelerate beams to above 200 MeV/u [2]. Because the acceleration gradient of the FRIB cavities goes up to 8 MV/m and the beam velocity increases from beta about 0.03 to 0.6 through the driver linac, the maximum velocity change in a single low beta cavity for a 2-pi phase scan can be above 10%, and the beam bunch structure may only survive a few meters downstream of the cryomodule, tuning of the cavity phase and amplitude is very difficult compare with that of a high energy linac. In this paper, SRF cavity phase and amplitude tuning algorithms are studied.

TUNING OF THE HWR CAVITY

In a RF linac for proton beam or heavy ion beams, Delta-T [3], and phase scan signature matching [4] techniques are widely applied to tune cavity phase and amplitude in which beam position/phase monitor (BPM) pairs are utilized to measure the absolute beam phase while scanning the cavity phase and amplitude; the synchronous phase as well as the acceleration gradient of the cavity can then be precisely determined by signature matching of the BPMs' time-of-flight (TOF) measurements against the RF cavity model. In this paper, we mainly focus on the applications of phase scan signature matching techniques.

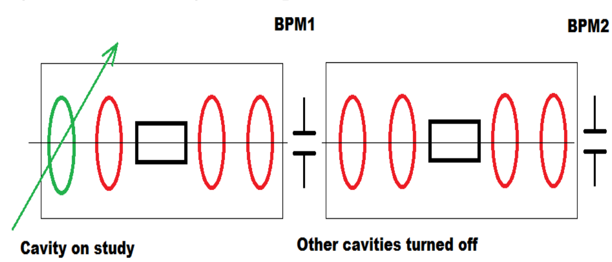

Figure 2: Schematic configuration of cavity phase scan

Figure 2 shows a schematic configuration of the cavity phase scan measurements. A pair of BPMs is downstream of the RF cavity on study, with all other cavities between the BPMs and the scanning cavity turned off, a 2-pi phase scan of the cavity is performed and the beam phase is recorded with the BPM pair. Because the beam current is low compare with that of a pulsed SRF linac such as the SNS, beam loading induced RF fields in the off cavities downstream may not significantly affect the measurements which is different to the SNS linac [5].

In the studies, IMPACT [6] is used for generation of the beam absolute phases exactly at the locations of the BPM pair. Then a thin-lens model of the RF cavity is applied:

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# zhangy@frib.msu.edu

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$$\Delta E = qETL \cdot \cos(\varphi_{rf} + \varphi_i) \quad (1)$$

where, q is charge state, and E acceleration gradient, T transit time factor, L is the effective length of the cavity.

Using Equation 1 and Open XAL - Extended accelerator language (XAL) – an open source Java based accelerator physics software toolkit [7], we fit the cavity model against the IMPACT simulated BPMs' data to search for the beam energy, the cavity acceleration gradient and the initial beam phase. Eventually, the synchronous phase and acceleration gradient of the cavity can be tuned up within an accuracy about ±1° in phase and about ±1% in amplitude.

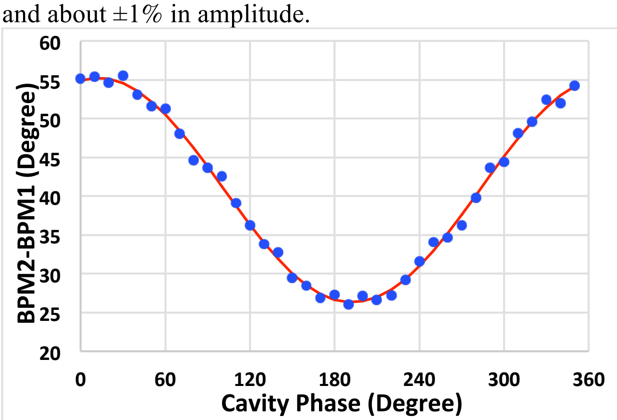

Figure 3: BPM phase differences in a 2-pi phase scan of a HWR cavity. IMPACT simulations (blue dots), and the solutions found with Open XAL and Equation 1 (red line).

For a uranium beam with charge state +78, and injection beam energy of 150 MeV/u, the design voltage gain of a HWR cavity is about 3.56 MV. Results of a cavity 2-pi phase scan is shown in Figure 3. Because the beam energy is not so low, distance of the BPM pairs should be sufficient for accurate TOF measurements; BPM1 is downstream the 1st cryomodule, and BPM2 downstream of the 3rd – a total distance about 12.4 meters in this case.

In the studies, ±2° random phase errors are assumed to the measurements with BPMs, and the initial beam phase is 172.2°. Open XAL solved results are: beam energy 150 MeV/u, voltage gain 3.52 MV, and beam phase 172.3° - it is satisfactory for the FRIB beam tuning requirements.

TUNING OF THE QWR CAVITY

As mentioned earlier, QWRs are designed to accelerate low energy beams. At injection of the linac, beam energy is merely about 0.5 MeV/u, the maximum particle velocity change in a single cavity 2-pi phase scan is more than 10%. It makes the phase scan signature matching techniques based on the simple thin-lens model invalid, meanwhile, bunch structure of the beams only survives a few meters downstream of the cryomodule, more BPMs are needed to tune low energy beams. Shown in Figure 4 is an IMPACT simulation results against thin-lens model of a beta 0.041 QWR cavity for a 2-pi phase scan, and it shows that the model is failed at low energy – 0.5 MeV/u in this case.

To address the problem of velocity changes in SRF gaps, higher order transit time factors may apply [8]. However, a simple and accurate method is to use step integrations to precisely track particle accelerations in RF gaps. Figure 5 shows a satisfactory result of using Open XAL for TOF signature matching with step integrations of the beta 0.041 QWR for a 2-pi phase scan against that of IMPACT.

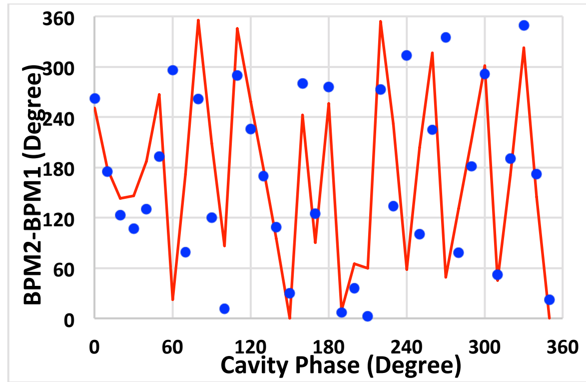

Figure 4: IMPACT simulation (blue dots) against thin-lens model (red line) for a beta 0.041 QWR in 2-pi phase scan.

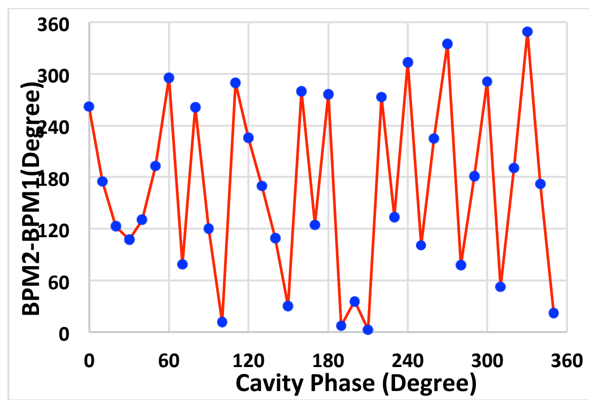

Figure 5: IMPACT (dots) against step integrations (line)

In reality, the situations of phase and amplitude tuning of low beta cavities are more complicated: in additional to the BPM phase errors, 2-pi phase aliasing issue, beam and RF jitters and drifts, there are other RF fields such as dipole and quadrupole components in the FRIB cavities [8] which are not negligible. Tuning of the cavity requires patience.

TUNING OF THE BUNCHER CAVITY

Longitudinal beam phase space matching is required at a few locations in the FRIB linac, such as the entrance of each linac segment – three of them, and the charge stripper. Matching cryomodules with buncher cavities are installed upstream of those areas for beam longitudinal matching.

Table 1. Bunch Length Simulation Study Results

Cav. (MV)	0.0	0.2	0.4	0.6	0.8	1.0
BSM (mm)	5.3	4.1	2.9	1.8	1.1	1.3
Found (mm)	5.3	4.1	2.9	1.8	1.1	1.3

To perform the matching, a bunch shape monitor (BSM) which is located close to the charge stripper will be used for bunch length measurements. After the cavities' phase and amplitude been properly tuned following the recipes discussed in the previous sections, a cavity amplitude scan is conducted: adjust the RF amplitudes of all the buncher cavities in the cryomodule, and measure bunch length with the BSM. The next step is using Open XAL search for the injection beam longitudinal parameters that reproduce the BSM measured bunch length, and results of a simulation study is shown in Table 1. Finally, we apply matching with Open XAL again to optimize the cavity amplitudes for the desired beam parameters on the charge stripper. Figure 6 shows the simulation results before matching, and Figure 7 is that after matching with the charge stripper at the end.

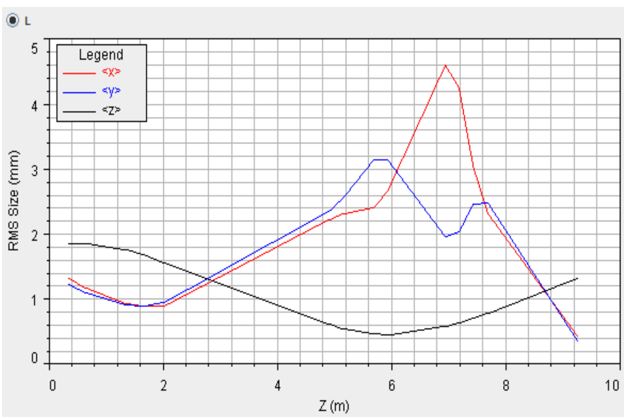

Figure 6: Beam RMS sizes before longitudinal matching (<x> and <y> in mm, bunch length <z> in degree)

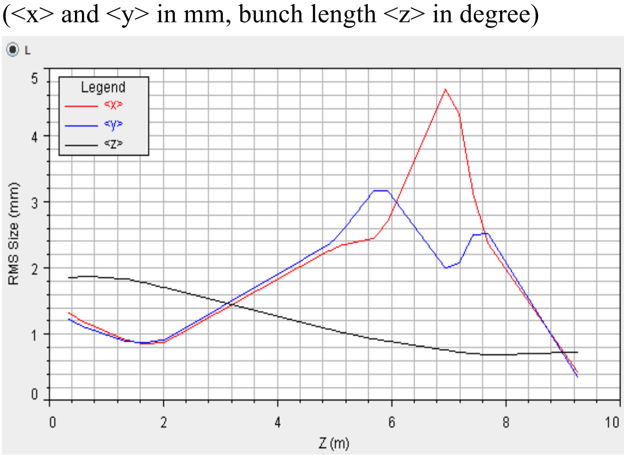

Figure 7: Beam RMS sizes after longitudinal matching

There are no errors assumed in the above simulations. However, when the matching is not crucial, error studies show that BSM measurements errors of ±10%, and SRF phase ±1° and amplitude ±1% errors are acceptable.

Because longitudinal matching for other areas are less crucial – at least suggested in the simulation studies, a few degree and a few present cavity RF errors are acceptable, therefore in principle, those cavities can be tuned similarly as all the acceleration cavities in the linac with phase scan and signature matching, and setup of the cavity phase and amplitude to the design should be sufficient. But even in the worst scenario when a longitudinal matching becomes necessary at other locations such as the entrance to each linac segment, we may apply longitudinal beam acceptance and emittance scan measurement technique, developed at SNS, which uses beam current monitors at the exit of the linac and beam loss monitors in the linac [10].

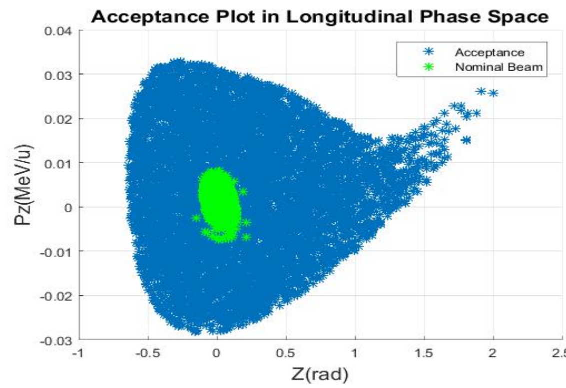

Figure 8: Longitudinal acceptance of linac segment 1.

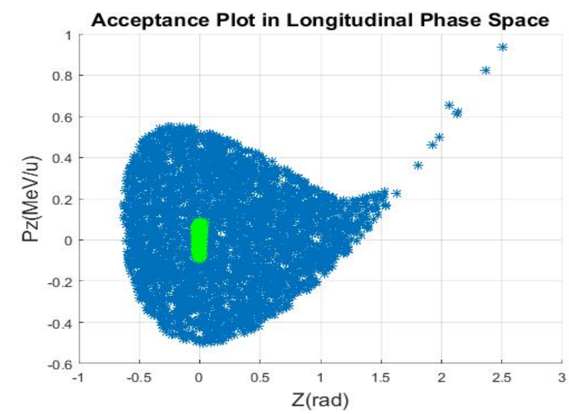

Figure 9: Longitudinal acceptance of linac segment 2.

IMPACT simulated beam longitudinal acceptances of the FRIB linac segments 1 and 2, are shown in Figures 8 and 9, respectively, and the nominal beams are also shown. Manipulating the injection beams in the longitudinal phase spaces, acceptance as well as emittance can be measured.

CONCLUSIONS

Phase and amplitude tuning algorithms of the FRIB cavities are studied, and the difficulties in dealing with the low beta SRF cavities are discussed. In this paper, we also introduced two different algorithms for longitudinal beam matching of the FRIB driver linac, and error analysis show that the linac design as well as the planned beam tuning algorithms satisfy the requirements to tune this unique SRF linac running for high power heavy ion beams.

ACKNOWLEGEMENTS

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