PHASE STABILITY OF THE RF REFERENCE LINE FOR THE FRIB LINAC*

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Abstract

The phase stability of rf reference line is usually quite restricted in a high energy linac (very long linac, very high frequency). Due to the change of the ambience temperature in the linac tunnel, the electrical length of reference rf cables may change significantly, which results in unacceptable phase changes in cavities. So, sometimes the reference line is very expensive, for example, made of optical fiber housed in a lengthy thermostatic chamber. The frequencies of FRIB linac cavities are 80.5 and 322 MHz (not very high). We also take advantage of the double-folded linac geometry and feed the reference line in the center of the linac to effectively reduced the reference line by 6 times. Our studies show that the FRIB linac can tolerate up to 12ps phase stability of the rf reference line. Therefore, no is needed for the reference line.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) [1], currently under establishment at the Michigan State University, will be a new national user facility for nuclear science. FRIB accelerator is a cw, high power, heavy-ion machine that will accelerate all stable isotopes to energies ≥ 200 MeV/u with a beam power of up to 400 kW. The driver linac consists of a front-end to generate ion beams and boost beam energy, a superconducting linac that is folded into three parallel segments and connected by a stripper station and two 180-degree bending sections, and a beam delivery system to transport output beam into the fragmentation target, as shown in Figure 1. The length of linac footprint is about 150m. Linac Segment 1 consists of 3 β=0.041 cryomodules and 11 β=0.085 cryomodules to increase the beam up to 20 MeV/u followed by a charge stripping system. All the cavities in Segment 1 are Quarter-wave Resonators (QWRs) with operating frequency of 80.5MHz. Half-wave Resonators (HWRs) with higher operating frequency of 322MHz are used for both Segment 2 and Segment 3. There are 12 β=0.29 cryomodules and 12 β=0.54 cryomodules in linac Segment 2 to accelerate beam energies ≥ 150 MeV/u. Additional 6 β=0.54 cryomodules in linac Segment 3 further push beam energies above 200 MeV/u, followed by a FODO quadruple lattice section that is reserved to place more cryomodules for future energy upgrade.

As a new generation national scientific user facility, the performance of FRIB has quite stringent requirements. Therefore, each system and its subassemblies become critical for the operation of such a complex machine. The rf field generated by cavities is one of the key factors that determine the beam performance of the linac. It is a challenging task to achieve good phase and amplitude regulation of the cavities in a large system. There are several types of errors or uncertainties related to the rf field of the cavities in linacs like the FRIB driver linac. For examples, (1) the random rf phase and amplitude fluctuation or jitter that changes very fast and dynamically and is regulated by low level rf controller, (2) misalignment of field axis with respect to the beam axis that is static and may be measureable thus be corrected or compensated, (3) deviation of amplitude settings with respect to the design that is static and determined mainly by calibration, (4) deviation of phase settings with respect to the design that is also static and usually more sensitive than that of field amplitude especially at low energy side, (5) phase change due to the variation of the electrical length of rf cable that is mainly due to thermal effect and thus a slow drift process. Therefore, each of them needs to be evaluated and controlled to meet requirements. In this paper, we discuss exclusively on the topic of the phase drift of the rf reference line for the FRIB linac.

CAVITY PHASE SETTINGS

There are total 330 cavities (including the rebuncher cryomodules between each segment) distributed in the three linac segments of the double-folded FRIB driver linac. All of the cavities (either QWRs or HWRs) have

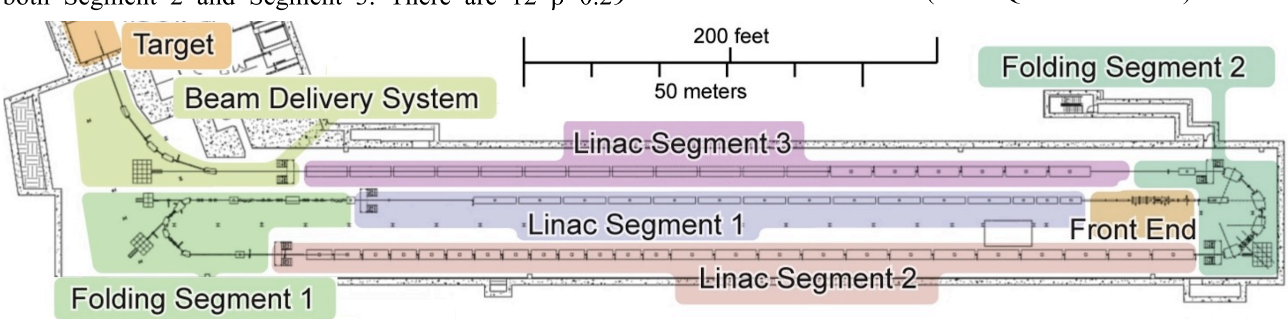

Figure 1: Layout of the FRIB driver linac.

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two accelerating gaps excited in π-mode (that means the change of the electric field between the gaps is always opposite but at the same rate). Each cavity is powered individually, thus the amplitude and phase of each cavity can be independently adjusted. The field amplitude of cavity is usually set as high as allowed for reliable operation, while the phase of cavity that the beam experiences when transiting through the cavity (called synchronous phase) is determined by the beam dynamics design of the linac lattice. In a real machine, each cavity must be phase-scanned at least one time with beam by typically measuring the energy change (ΔE) as a function of the phase (φ), as illustrated in Fig. 2. The phase that corresponds the maximum energy is defined zero degree, and thus the synchronous phase φ_s (generally around -30º to tradeoff between the acceleration efficiency and the size of rf bucket) is set by retracting $|\varphi_s|$ degrees from the "zero". Once the synchronous phase is found, the low level rf controller will lock it. This procedure will be applied every cavity sequentially along the beam path. The synchronous phases of all cavities must be well-controlled over a long period of operation, so beam can always be accelerated along the linac synchronously in the stable region.

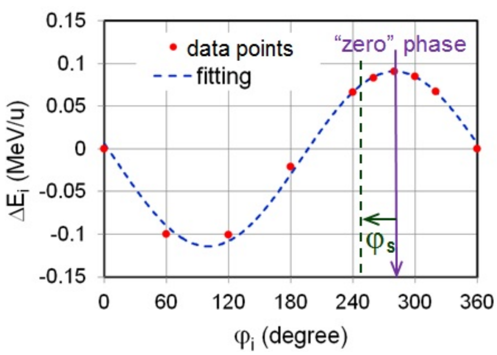

Figure 2: Phase scan of a β=0.041 QWR with uranium beam (q/A=33/238) at 0.5MeV/u to set the synchronous phase of the cavity.

RF REFERENCE LINE

The phase stability of rf reference line is usually quite restricted in a high energy linac where the linac is not only very long but also operates at high frequencies. High performance coaxial cables are widely used for rf reference line. It is well known that phase change in coaxial rf cables is sensitivity to the ambience temperature variations (due to the change of electrical length). So, sometimes the reference line is very expensive, for example, made of optical fiber housed in a lengthy thermostatic chamber. The global temperature at the FIRB linac tunnel will be controlled in the range of 72±6 ºF (22.2±3.3 ºC), which mainly implies some areas (e.g. near room temperature magnets) can have slightly higher temperature while other ones (e.g. near cryomodules) slightly lower. However, long-term temperature drift at a given location during normal operation will normally be much smaller than ±6 ºF.

A typical rf coaxial cable is a composite structure that consists of metal conductors separated by a polymer dielectric. The entire assembly is encapsulated with a polymer jacket. The phase length in degree of such a cable is given by

$$\varphi = \frac{360 f_0 \cdot l \cdot \sqrt{\varepsilon_r}}{c} \qquad (1)$$

where c is the velocity of light in vacuum, f_o is the signal frequency, l is the mechanical length of the cable and ε_r is the dielectric constant of the insulating material between the center and the outer conductor of the coaxial cable. Therefore, for a given rf frequency (f_o), the phase change depends on the change of physical cable length (l) and/or the net dielectric constant of the propagation medium (ε_r). The metal conductor changes linearly with temperature, but the behavior of dielectric constant is usually very complicated when the temperature of cable changes.

The FRIB reference line will provide a stable signal of 10.0625 MHz which is compatible with rf system frequencies of 20.125, 40.25, 80.5, 120.75, 161, and 322 MHz. To minimize the temperature related phase change, the reference clock is fed from the center of the linac tunnel into six rf distribution lines through a 6-way splitter, as shown in Fig. 3. In this scheme, the reference line is effectively reduced by 6 times. The length of each linac segment is no more than 140m, so each rf reference line is about 70m long. In addition, low loss, phase stabilized cable (RFS 7/8" LCF78-50J) is selected for the rf reference lines. Foam polyethylene instead of polytetraflouoroethylene (teflon) is used as the insulating material in the cable to avoid the so-called teflon "knee" induced phase instability problem [2] (teflon itself undergoes a quick structural transition around 19 ºC, which results in a rapid change in the dielectric constant and thus an abrupt change in phase length).

To check the relation of phase change with temperature, a 136.8-meter-long coaxial cable (RFS 7/8" LCF78-50J)

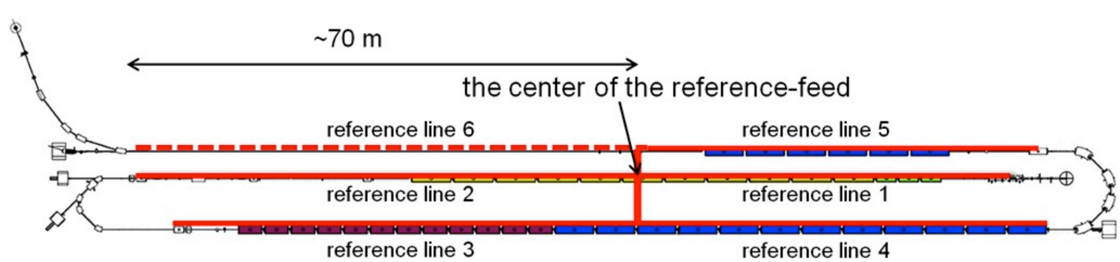

Figure 3: Schematic layout of the reference lines and the center of the reference-feed in the linac tunnel.

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from Radio Frequency System (RFS) company, same type as those to be used in FRIB linac, was tested at the FRIB lab with a 10.0625 MHz signal. The cable was rolled up and placed in a room where the temperature can be adjusted and controlled, as shown in Fig. 4. The oscillator, phase detectors and other devices were set up right outside the room, and can be seen through the window. Phase change of 0.105 degrees with respect to 10.0625 MHz was measured between the two different temperatures of 70.3 and 79.8 ºF, which is similar to the expected ambient temperature range within the FRIB linac environment.

Figure 4: Setup of the reference cable test at FRIB lab.

BEAM DYNAMICS STUDY

Beam dynamics study was performed to evaluate the FRIB linac performance with rf phase changes caused by the thermal effect of the rf reference lines. Based on the measured data, for a 100-meter-long cable and 1 degree Fahrenheit temperature increase, total phase change will be 0.06465 degrees at 80.5 MHz. Since the FRIB specs of the global temperature variation within the entire tunnel is 72±6 °F, cable temperature change of 12ºF is assumed in the study. Although this will unlikely happen, because the coherent change of the entire tunnel temperature should be much less than ±6 °F. So, the phase change of each cavity is calculated and shown in Figure 5, where the phase in degree corresponds the rf frequency of each cavity (80.5 MHz for QWRs, 322 MHz for HWRs).

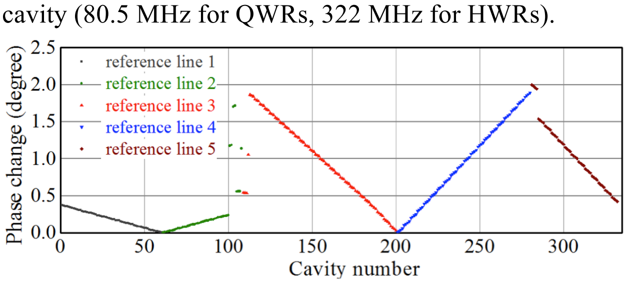

Figure 5: Phase change (“degree” corresponds to the cavity rf frequency) for each of the cavity along the linac.

Multi-charge-state uranium beam [3] carried from the frontend was tracked through the entire linac to the target. The results show the amount of phase change (shown in Fig. 5) is not sensitive to the beam performance. Sampled particle distributions on target are plot in Fig. 6 with the cases of phases changed and unchanged, which indicate the overall impact is insignificant. Although the maximum phase change is ~2 degrees for the HWRs in Segment 2 & 3, and ~0.5 degrees for the QWRs in Segment 1, the phase change between the neighbouring cavities is coherent and very small (unlike rf jitter), the particles still well follow the betatron oscillation in the longitudinal stable region. The amplitudes of the centroid oscillation in longitudinal phase space are negligible, as shown in Figure 7.

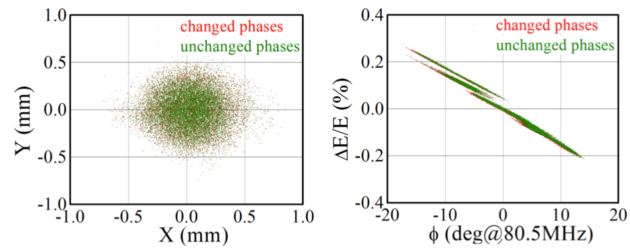

Figure 6: Sampled particle distributions on target with (in red) and without (in green) the phase changes. Both transverse (left) and longitudinal (right) are very similar for the two cases.

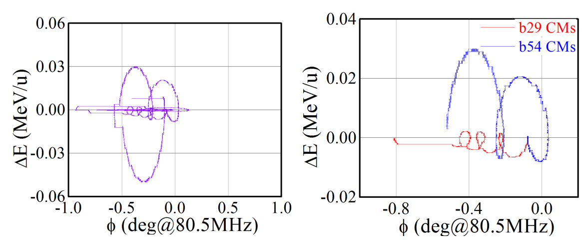

Figure 7: The centroid motion in longitudinal phase space with phase change included for the entire linac (left). Zoom of the Segment 2 only (right). The amplitudes of the oscillation are negligible.

SUMMARY

FRIB will feed the reference clock from the center of the linac tunnel into six rf distribution lines. The long-term thermal related phase change of each line shall be less than 12 ps. Beam dynamics studies using measured data confirm that the phase stability of the rf reference cable meet the requirement.

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