RF CAVITY PHASE CALIBRATION USING ELECTROMAGNETIC PICKUPS*

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Abstract

A method is presented using electromagnetic pickup probes for RF cavity phase calibration. (We used capacitive style pickup probes.) Pickup probes provide fast readings, and measurements of the phase difference between a pair of pickup probes provides enough information about the phase-energy curve to yield a fit for the zero-crossing phase. We present an overview of the algorithm and measurement results of an implementation on the ReA3 reaccelerator.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) is a heavy ion fragmentation facility to produce rare isotopes far from stability for low energy nuclear science. The facility will utilize a high-intensity, superconducting heavy-ion driver linac to provide stable ion beams from protons to uranium at energies greater than $200\ \mathrm{MeV/u}$ and at a beam power of up to $400\ \mathrm{kW}$ [1]. The baseline design for the linac comprises over 300 accelerating superconducting cavities. A precondition for tuning the linac is calibrating the radio frequency (RF) phase of each of these cavities, which requires a phase scan combined with energy measurements. With such a large number of cavities as it is planned for FRIB, a need arises for an automated approach to calibrating cavity phase.

RF cavity phase calibration is the process of calibrating the cavity phase relative to the phase of the accelerated beam. For this purpose, the zero-crossing phase points (the phase points at which the cavity does not provide any acceleration) are determined. There are two such points in a full 360-degree phase range (180° apart from each other), and we use the one on the bunching side of the phase slope as the reference. The value of the zero-crossing depends on the beam energy, thus the cavities need to be calibrated for every new energy tune. Therefore, cavity phase calibration is a necessary recurring task in operations.

We approached the concrete problem of calibrating the cavity phases on the ReA3 accelerator at Michigan State University [2], which is currently being commissioned. Prior to the installation of Beam Position Monitors (BPMs) in the ReA3 accelerator, the only method available for cavity phase calibration was energy measurements from silicon foil detectors. As these measurements are inherently slow, calibrating the six accelerating cavities currently installed in ReA3 could take up to several hours. Since capacitive style electromagnetic pickup probes provide fast readings, we explored the application of pickup probes for inferring the beam energy and thereby calibrating cavity phase. The capacitive style pickup probes we used were the two BPMs installed on the ReA3 beam line. The details of the BPMs in the ReA3 accelerator are presented in Rodriguez et al. [3]. The phase readouts were averaged over the four buttons for each BPM, so that for this purpose, the BPMs were effectively used only as electromagnetic pickup probes.

PRINCIPLE

The readouts from two pickup probes separated by a certain distance provide the phase difference of bunches at the two locations. It is important to keep in mind, though, that this is not the absolute phase difference, but its value modulo 360°. In other words, the pickup probes do not provide information about the total number of bunches between the two locations, but only the fraction of the RF period that represents the "incomplete last bunch." The number of "complete bunches" between the two locations needs to be evaluated by other means. As will be shown, however, knowing this information exactly is not essential for the applicability of the method we are presenting.

The phase difference $\Delta\varphi$ between the pickup probes can be translated into the time of flight via

$$t(\Delta\varphi; n) = T_{RF}\left(n + \frac{\Delta\varphi}{360^\circ}\right), \qquad (1)$$

where n is the truncated number of bunches between the pickup probes, T_{RF} is the RF period, and t is the time of flight. The integer n decreases with beam energy, and within energies attainable in the ReA3 accelerator (without deceleration), and with the BPMs separated by $2.08\ \mathrm{m}$, it ranges from 14 (for the beam energy after the RFQ of $600\ \mathrm{keV/u}$) to 8 (for the maximum beam energy after the linac of $1.9\ \mathrm{MeV/u}$). Translating the time of flight (1) into energy (non-relativistically), we obtain the dependence of energy per nucleon E/m on the phase difference $\Delta\varphi$:

$$\frac{E}{m}(\Delta\varphi; n) = \frac{1}{2}\left(\frac{L f_{RF}}{n + \frac{\Delta\varphi}{360^\circ}}\right)^2, \qquad (2)$$

where L is the distance between the pickup probes, and $f_{RF} = 1/T_{RF}$ is the RF frequency. Equation (2) can be in-

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verted eliminating the unknown number of bunches n into

$$\Delta\varphi(E) = \left(360^\circ L f_{RF}\sqrt{\frac{m}{2E}}\right) \mod 360^\circ. \quad (3)$$

This functional dependence, for the relevant range of energies, is shown in Figure 1, which is a graph we refer to as a *mod-360 hyperbola*.

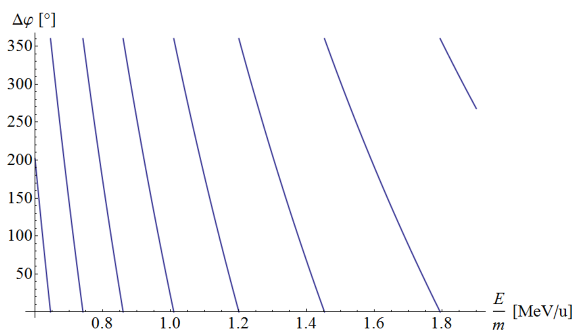

Figure 1: Bunch phase difference at pickup probes $\Delta\varphi$ as a function of beam energy per nucleon E/m. ($L = 2.08$ m)

In the method presented here, the beam energy is varied by changing the cavity phase

$$E(\Phi) = E_0 + QeV \sin(\Phi - \Phi_0), \quad (4)$$

where Φ is the cavity phase, E_0 and Φ_0 are the zero-crossing energy and phase, respectively, Q is the beam charge state (an integer), and eV is the cavity amplitude. The dependence $\Delta\varphi(\Phi)$ of the measured phase difference on the cavity phase (the independent variable) is therefore obtained by composing the sine function $E(\Phi)$ (4) with the mod-360 hyperbola $\Delta\varphi(E)$ (3). Ideal measured data (pickup probes phase difference vs. cavity phase) should therefore be aligned along the curves shown in Figure 2. Note that this plot is not a broken sine function inasmuch as the mod-360 hyperbola $\Delta\varphi(E)$ (3) is not a broken line (cf. Figure 1).

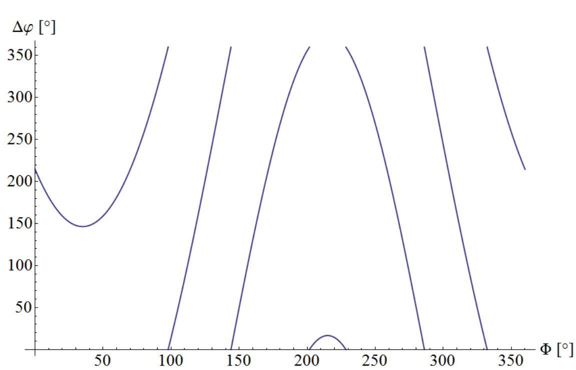

Figure 2: Ideal measured data: pickup probes phase difference $\Delta\varphi$ as a function of cavity phase Φ. ($E_0 = 600$ keV, $eV = 100$ keV, $\Phi_0 = 305°$, $L = 2.08$ m)

Algorithm Outline

The first step in fitting for the sought parameter Φ_0 is to turn data in the form of $\Delta\varphi(\Phi)$ into a continuous-looking function, effectively a "reverse mod-360" operation. We refer to this process as *stitching*. Once the data are stitched, ordinate values are no longer restricted to a 360° window. Next, we eliminate the unknown parameter n from consideration by picking a reasonable estimate for it, and transforming the phase difference data into energy values. Then, we fit the sine curve $E(\Phi)$ (4), which yields three fitted parameters (E_0, eV, Φ_0) including the wanted zero-crossing phase Φ_0. An error in the estimate for n is mostly reflected in the error in E_0, while the effect on the fit in Φ_0 is negligible, as evidenced by numerical trials on measured data.

METHODS

The algorithm as outlined above was implemented in Python, with a curve fitting optimizer provided by the SciPy [4] *optimize* package and a graphical user interface (GUI) written using the *Traits* and *TraitsUI* packages, also included in the SciPy library. The EPICS [5] connection was established via PyEpics [6], which allowed the software to do a fully automated phase scan by setting cavity phase values, and reading cavity phase readbacks and BPM phase data, as well as any other EPICS channels that might be of interest (e.g. Faraday Cup readouts for beam intensity).

In order to be of practical use, in addition to the basic phase scan controls, data collecting, and fitting capabilities, the software also required data resampling functionality to produce meaningful fits. For various reasons, some measured data points need to be discarded. The most commonly observed cause of outliers in the ReA3 accelerator data was sparking between bender plates near the source, due to the fact that the source needs to operate in a high current mode in order for the pickup probes to provide a sufficient signal throughout the phase scan. Sparks would typically produce a single bad datapoint before the beam falls back into its trajectory. We were carrying out several measurements (typically 10, although in some instances 3 were sufficient) for each cavity phase, and such outliers were easily detectable due to a large deviation from the mean. However, other causes of error in the measurements lead to an entire set of measurements for a given cavity phase setpoint (referred to as a setpoint group) to be discarded, either because of a large rms, or as too far removed from the fitted curve. Therefore, the resampling was done at two levels: (1) within a setpoint group: removing single data points that are too far from the mean; (2) among setpoint groups: removing entire setpoint groups whose standard deviation is too large, or whose mean is too far from the fitted curve.

As far as the beam line configuration, we note that the locations where the BPMs were installed in the ReA3 accelerator were not chosen with this particular purpose in mind, and were less than ideal: they were about 0.6 m down-

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stream from the last accelerating cavity with no focusing or steering elements after the cavity, and separated by a distance of $2.08\ \mathrm{m}$. These were the only two BPMs available, and so were used for all the cavities. The upstream cavities were therefore more challenging due to their greater distance from the BPMs.

RESULTS

Several test runs of the software were carried out on the ReA3 accelerator. The beam used in each case was molecular hydrogen $H_2{}^+$. The issue that made the calibration process slow at first was the tuning required to prepare the beam, which was not trivial due to the position of the BPMs and the lack of focusing and steering elements around them. Moreover, in order to obtain usable data, the beam must be tuned so as to provide a good signal from the BPMs throughout a full cavity scan. This is complicated by the fact that due to the design of the ReA3 superconducting RF cavities, they steer the beam as a function of phase setting [7]. Tuning was more challenging with the upstream cavities due to the greater distance to the BPMs and because of the effect of the cavity kicks is proportionately larger on the lower energy beam at the beginning of the linac. In the first runs, tuning was taking up to a few hours per cavity. As the tunes were developed, this time was significantly reduced, and in the last run tuning was taking an average of about 10 minutes per cavity.

We have empirically verified the claim presented above that the fit for the zero-crossing phase is not affected by an inaccurate estimate of the number n of bunches between the pickup probes. For all the measured data, varying n between extreme values attainable in ReA3, the resulting change in the fitted zero-crossing phase Φ_0 is less than $0.1°$, which is less than the estimated accuracy of the method.

In the last run, carried out in September 2013, we have developed a procedure to phase the linac sequentially, using the fitted zero-crossing phase value of the last cavity to set the cavity phase to nominal acceleration phase (in ReA3: $-20°$ off peak) before proceeding with the next one. The energy plot of the data for one cavity (after resampling), along with the fitted sine curve, is shown in Figure 3.

CONCLUSION

A method for calibrating cavity phase using two capacitive style pickup probes by measuring the relative difference in phase between the two pickup probes was presented. No other measurements are necessary: the method does not require absolute energy measurements, since a reasonable estimate of the number n of bunches between the pickup probes is sufficient to yield an accurate fit for the zero-crossing phase Φ_0. The principle is based on simple equations: phase difference data are stitched together and transformed to the energy domain, where a sine function is fitted, and the abscissa offset represents the desired parameter Φ_0.

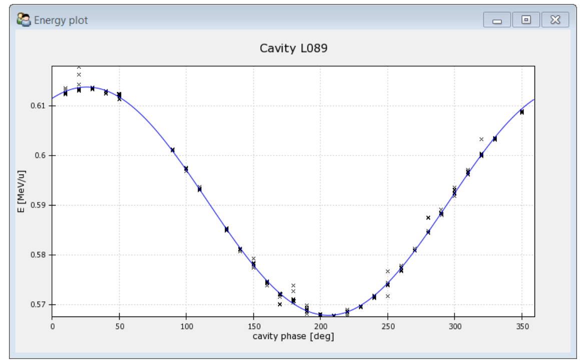

Figure 3: A screenshot of a window of the cavity phase calibration software that shows energy vs. cavity phase data (black) with the fitted sine curve (blue) for one of the accelerating cavities in the ReA3 linac.

This algorithm was implemented and tested on the ReA3 accelerator. The implementation software had a direct connection with EPICS channels, automating the full cavity scan process, and it included data resampling features to deal with unacceptable levels of noise in the data. In the best case, a usable full cavity scan took only a couple of minutes, however this time is dominated by the time needed to tune the beam in order to prepare it for the scan. The latter time is strongly dependent on the position of the pickup probes relative to the cavity, and their separation distance, as well as the availability of tuning and focusing elements, and the reproducibility of previously developed tunes, all of which were less than ideal in our case. We still successfully calibrated the accelerating cavities in the ReA3 accelerator using BPMs as pickup probes.

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