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Abstract

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Full Text

Preamble

Automatic Phase Setting via Time-of-Flight Alignment and Phase Calibration on a Superconducting Hadron Linac

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Automatic phase setting is essential for modern linacs that face increasingly stringent time demands for beam tune-up and fault compensation. A key challenge in automatic phase setting is obtaining accurate knowledge of the position and phase offsets of all cavities. This study proposes a beam-based method that employs time-of-flight (TOF) experiments for simultaneous alignment and phase calibration of a superconducting hadron linac. The proposed method is verified using the CAFe II accelerator at the Institute of Modern Physics, where offset measurements enable rapid tune-up via automatic phase setting, and the output beam energies closely match predicted values. The method can address longitudinal position shifts within cryomodules due to cool-down, is readily applicable to superconducting hadron linacs, and is expected to be employed in the upcoming commissioning of CiADS and HIAF.

Keywords: Linear accelerators, Beam position monitor, Heavy ion accelerators

Introduction

Hadron linear accelerators (hadron linacs) are crucial scientific instruments with significant applications across many fields. Examples include PIP-II [1] for pursuing the intensity frontier in particle physics; FRIB [2] and TRIUMF [3] for rare isotope production in experimental nuclear physics; SNS [4], ISIS [5], J-PARC [6], CSNS [7], and ESS [8] as spallation neutron sources for materials research; numerous machines for nuclear medicine [9, 10]; and CiADS [11, 12] as a demonstration of an accelerator-driven system in advanced nuclear energy. In the 21st century, research linacs have increasingly utilized superconducting cavities, which have lower operating costs than normal-conducting cavities and enable high-current operation [4, 13].

Linacs employ independently phased resonant cavities to accelerate beam particles. During linac tune-up, each cavity must be phased correctly so that beam particles arrive at each cavity during the design phase, thereby achieving the designed energy profile and ensuring stable longitudinal dynamics. This phase-setting or turn-on problem has been a long-standing challenge for linacs because uncertainties in relevant beam and cavity parameters can render direct model-based calculations unfeasible.

A conventional solution to the phase-setting problem is a cavity phase scan [14, 15] at the beginning of each linac tune-up. Although cavity phase scans require limited initial knowledge and accommodate many common uncertainties, cavities can only be set up individually, with each cavity requiring several minutes to configure. In superconducting linacs, where the number of independently phased structures is typically larger for a given energy gain [16], tune-up via phase scans is a time-consuming procedure that can take several hours.

To satisfy demands for rapid beam tune-up, automatic phase setting is emerging as a new technique for modern superconducting linacs, such as those at SNS [17], FRIB [18], and TRIUMF [19]. Automatic phase-setting capabilities are a prerequisite for rapid online fault compensation [20, 21], which is essential in applications such as accelerator-driven systems that require efforts to limit beam trip duration and boost reliability.

Automatic phase setting relies on alignment and phase calibration techniques to obtain sufficient knowledge of relevant linac parameters, enabling input phase values to be obtained from model calculations. This allows a superconducting linac to be configured in minutes and significantly accelerates tune-up. The conventional method involves obtaining required position information separately via surveys or monitors [22] and phase information via calibration experiments.

This study proposes a beam-based method that employs time-of-flight (TOF) experiments to simultaneously determine cavity and beam position/phase monitor (BPM) positions in addition to cavity phase offsets. This method is particularly useful for implementing automatic phase setting in superconducting linacs because it can account for longitudinal position shifts of cavities and BPMs within cryomodules (CMs) during cool-down, which may significantly affect the accuracy of phase calculation models.

The remainder of this paper is organized as follows. Section II elaborates on the phase-setting problem and its relevant parameters, followed by a discussion of two potential solutions: cavity phase scan and automatic phase setting. Section III describes a set of alignment and calibration experiments based on TOF measurements and data analysis that enable beam-based calibration of both cavity positions and cavity phase offsets. Section IV reports results from an experiment at the CAFe II accelerator and the successful application of calibration results to automatic phase setting. Section V presents conclusions and proposals for further research.

Phase-Setting Problem

Cavity Phase upon Beam Arrival

For a given cavity, the relationship between the set phase ϕ_{set} and the phase of the cavity when the beam arrives ϕ_{in} is given by:

$$\phi_{\text{in}} - \phi_{\text{RF-ref}} = \phi_{\text{set}} + \phi_{\text{offset}} - n \times 360^{\circ},$$

where $\phi_{\text{RF-ref}}$ is the phase of the radiofrequency (RF) reference line when the beam arrives at the cavity and ϕ_{offset} is the phase offset caused by the low-level RF system.

The phase-setting problem involves finding the correct ϕ_{set} for each cavity such that the corresponding ϕ_{in} equals the value in the beam dynamics design. As shown in Eq. (1), setting ϕ_{set} for a given target ϕ_{in} requires knowledge of ϕ_{offset} and $\phi_{\text{RF-ref}}$. $\phi_{\text{RF-ref}}$ is highly sensitive to differences in upstream beam conditions between runs. Therefore, phase-setting is not a one-off problem that can be solved by reusing ϕ_{set} once a successful run is achieved. At the start of each new run, ϕ_{set} for each cavity must be correctly reset according to unique beam conditions.

ϕ_{offset} is often assumed to be a fixed parameter in the absence of hardware changes. Under this assumption, ϕ_{offset} must only be measured once per hardware setup; however, it is currently unfeasible to measure it directly electronically. In practice, ϕ_{offset} experiences small drifts during day-to-day operation, particularly in older facilities. Such time drifts introduce additional errors in future phase settings after ϕ_{offset} is calibrated. As an ongoing research subject, recent advances include time-drift-aware optimization techniques based on machine learning [23, 24], but this problem is beyond the scope of this study. Time drifts in ϕ_{offset} are ignored in the following sections.

The description above uses ϕ_{in}, the cavity phase when the beam reaches the entrance of the cavity, which can be taken as the upstream end of the cavity fringe fields. ϕ_{in} is selected rather than the synchronous phase ϕ_s because the former is unambiguous. Although ϕ_s is part of the standard description in basic treatments of beam acceleration and longitudinal dynamics, it has different possible definitions once the constant-velocity assumption no longer holds within the cavity, and such an ideal assumption operates poorly in hadron linacs, particularly in the low-beta section. To avoid obtaining details for defining ϕ_s, only the calculation of ϕ_{in} is discussed. This treatment does not affect the utility of the results because regardless of the definition of ϕ_s, given the incoming beam energy and cavity field distribution, ϕ_s can always be calculated from ϕ_{in}. Considering the existence of such a conversion, only ϕ_{in} is used in this study.

Relevant Parameters and Uncertainties

For a new superconducting linac, typical knowledge about relevant parameters of cavities and BPMs in CMs is shown in Table 1 . BPMs are standard diagnostic devices that can return both the transverse position and arrival phase of a beam up to a fixed phase offset relative to the RF reference line [25]. The BPM parameters are crucial because phase-setting is typically resolved with measurements from BPMs installed along the entire linac [26].

The phase offsets of cavities and BPMs are completely unknown, whereas uncertainties in the longitudinal positions of cavities and BPMs, caused by structural displacements in the CM during cool-down, are estimated assuming that intra-CM position monitors are absent. These values are close to typical tolerances for longitudinal displacements [27, 28] or cavity phases [29] in CMs. Note that these two tolerances can be approximately converted by simply exchanging mm with °. Suppose the beam velocity is in the $\beta = 0.1$ regime, where the cavity frequency is typically ≈ 100 MHz. A longitudinal displacement of 1 mm then approximately corresponds to a phase error of 1.2° because:

$$\frac{10^{-3}\,\text{m}}{0.1 \times 3 \times 10^{8}\,\text{m/s}} \times 10^{8}\,\text{Hz} \times 360^{\circ} = 1.2^{\circ}.$$

If frequency jumps in higher-β structures downstream are accounted for, this relationship continues to hold up to factors of two to three, which is sufficient to corroborate the uncertainties in longitudinal positions listed in Table 1.

The cavity voltage coefficients provide the ratio between the set and true voltages, which is typically in the neighborhood of unity. These coefficients are also required to set up beam acceleration correctly, but they are fixed parameters that can be obtained from one conventional phase scan and thus are significantly less challenging than phase-setting.

Cavity Phase Scan

A widely used technique for resolving the phase-setting problem is the cavity phase scan [14], where ϕ_{set} corresponding to the desired ϕ_{in} is found without explicit knowledge of $\phi_{\text{RF-ref}}$ and ϕ_{offset}. This is achieved by scanning the operating phases of the cavities, recording the phases of the beam upon reaching downstream BPMs, and obtaining a sine-like curve that represents the cavity-BPM phase relationship, often referred to as the phase scan signature. Next, in a procedure often called signature matching, mathematical modeling is employed to determine the cavity voltage and ϕ_{in} [15], and occasionally the incoming beam energy, under the criterion that the modeled curve fits the phase scan results. If information from a single phase scan is insufficient, the scan is repeated at different cavity voltages to obtain better fitting results.

In the two-BPM version of the cavity phase scan [14, 30], the only requisite knowledge is the relative distance between the two BPMs downstream of the cavity, where the relative phase difference upon beam arrival is used to obtain the cavity-BPM phase relationship. The exact position of the cavities, z_{cav}, is not required in the calculations, which avoids the problem of displacements within CMs due to cool-down.

A cavity phase scan is performed sequentially through the linac, cavity by cavity. Hence, the larger the number of cavities, the longer the process. Even in linacs where automatic phase-setting is implemented, a cavity phase scan is often an indispensable step in the calibration stage.

Automatic Phase-Setting

As phase scans are time-consuming, many linac facilities, notably SNS and FRIB, have developed methods to tune up the linac without phase scans, which can reduce tune-up time by two orders of magnitude, from \$ \$10 h to \$ \$10 min [18, 31]. In these methods, a beam-based TOF calibration experiment [32] involving a phase scan alongside additional BPM measurements is first conducted to calculate ϕ_{offset}. Once all ϕ_{offset} values are known, they can be employed to accurately calculate $\phi_{\text{RF-ref}}$ in each cavity, thereby achieving automatic phase-setting in each subsequent tune-up. Both calibration and automatic phase-setting require good knowledge of cavity positions provided by alignment surveys.

Table 2 presents a comparison of different solutions that employ BPM phase information for the phase-setting problem. The proposed method is listed in the rightmost column, where both cavity and BPM positions are obtained via TOF alignment. A method that simultaneously performs alignment and phase calibration is introduced in the following section.

TOF Alignment and Phase Calibration

Linac Setup

To apply the TOF alignment and calibration method, the linac setup must fulfill two requirements [33]. First, there must be a pair of BPMs not far downstream of every cavity to enable conventional phase scans. As conventional phase scans are compulsory in modern hadron linacs, this requirement is always satisfied. Second, there must be an energy measurement device downstream of the last cavity, normally in high-energy beam transport (HEBT), which follows the superconducting section. In this study, energy measurement was assumed to be performed via TOF on a pair of BPMs dedicated to this purpose. This is the most common and practical setup used for accelerated hadron beams. The method still applies if energy is measured using other means.

All quantities listed in Table 1 were determined via TOF experiments and subsequent data analysis. Once obtained, they do not need to be measured again unless the linac hardware changes.

It is noteworthy that this TOF alignment and calibration method is applicable only to hadron linacs. As electrons are highly relativistic, each superconducting cavity can create only minuscule velocity changes, and the resulting differences in TOF measurements are far below the noise level of phase monitors.

Calibration Experiment

The calibration experiment comprised two steps. The first step was a forward phase scan that moved forward through the entire linac and performed a phase scan on each cavity. Conversely, the second step was a backward voltage scan that conducted a voltage scan on each cavity from the exit to the entrance.

Forward Phase Scan The goal of the forward phase scan is to set the phase of each cavity so that it accelerates the beam and provides proper longitudinal focusing. Even though detailed information about cavities and BPMs is not present at this stage, a preliminary beam dynamics design can be created based on prior knowledge of cavity and BPM positions. Based on this design, an empirical approach can be applied to perform phase scans in the following manner. Starting from the first cavity:

1. Scan the cavity phase ϕ_{set} over 360° and measure the arrival phases of the beam ϕ_a and ϕ_b at the two nearest downstream BPMs. Record ϕ_a and ϕ_b as a function of ϕ_{set}.

2. Plot ϕ_{set} vs $\phi_b - \phi_a$, adding or subtracting appropriate multiples of 360° at each $\phi_b - \phi_a$ to ensure a sine-like curve.
3. Set ϕ_{set} to a phase that is $|\phi_{\text{in}}|°$ smaller than the trough of the sine-like curve, where ϕ_{in} is given by the beam dynamics design.
4. Repeat steps one to four at the next cavity until the last cavity is reached.

This assumes that the voltage coefficient is one. From Table 2, the voltage coefficient is typically close to one; therefore, deviations of the true voltage from the design voltage should be acceptable for accelerating the beam through the linac.

In the last cavity, BPMs dedicated to TOF energy measurements can be utilized to perform the phase scan. Note that in step two, the cavity phase ϕ_{set} must be scanned over an interval sufficiently small to reconstruct a sine-like curve without ambiguities in step three. The typical interval is 10°. ϕ_{set} is also scanned over 360° to ensure that ϕ_{set} vs $\phi_b - \phi_a$ is 360° periodic in ϕ_{set}, thus avoiding errors in the multiples of 360° added or subtracted in step four.

It is possible to attempt TOF energy measurements throughout the forward phase scan and record the results. However, most results would probably be unreliable owing to poor longitudinal focusing of the beam during a phase scan. Hence, a backward voltage scan is also required to accumulate sufficient data for calibration.

Backward Voltage Scan The goal of the backward voltage scan is to measure the TOF of the beam at several energy values. The cavity voltage, rather than the cavity phase, is scanned to vary the energy while maintaining a longitudinal focusing effect, such that the bunch can be kept sufficiently short for TOF measurements as far downstream as possible. Using the linac configuration established by the forward phase scan, the backward voltage scan proceeds as follows. Starting from the last cavity:

1. Decrease the voltage of the cavity in discrete amounts down to zero. At each voltage value, record the TOF velocity and phase measurements of all downstream BPMs over multiple pulses.
2. After recording data at zero cavity voltage, turn off and detune the cavity to prevent interference with the beam energy in subsequent measurements.
3. Repeat steps one and two at the cavity upstream, and conclude the experiment after the voltage scan is performed on the first cavity.

Throughout the backward voltage scan, the transverse focusing and steering are adjusted as required to ensure proper beam transport.

The maximum bunch length required by TOF energy measurements varies with experimental conditions, such as beam current and beam energy. As an example, in the experiment described in Sec. IV B, the RMS bunch length should not exceed 50°.

Data Analysis

The measurement results from the calibration experiment were analyzed in several steps, with each step depending on analysis in previous steps. The analysis provides the relative positions and relative phase offsets between all cavities and BPMs in the linac. Section II.D addresses whether absolute positions and phase offsets are required and how calibration results can be utilized to achieve automatic phase-setting.

BPM Positions and Phase Offsets The results from the backward voltage scan were first used to obtain the relative positions and phase offsets between pairs of BPMs. For any pair of BPMs, denoted by BPM-a and BPM-b, with the latter located downstream, the measured phases and TOF measurements at the end of the linac are related by:

$$t_b - t_a = \frac{l_{\text{TOF}}}{t_{\text{TOF}}},$$

where l_{TOF} and t_{TOF} are the distance and passage time, respectively, between the two BPMs used for TOF measurements; t_b and t_a are the arrival times of the beam at BPM-b and BPM-a, respectively; and l is the distance between the two BPMs.

The relationship between BPM phase readings and time is as follows:

$$\begin{aligned}\phi_a &= t_a f \times 360^\circ + \phi_{a,\text{offset}} \\ \phi_b &= t_b f \times 360^\circ + \phi_{b,\text{offset}},\end{aligned}$$

where f represents the BPM frequency, and $\phi_{a,\text{offset}}$ and $\phi_{b,\text{offset}}$ indicate the phase offsets of the BPMs relative to the reference signal. Substituting $\Delta\phi = \phi_b - \phi_a$ into Eq. (3) yields:

$$\frac{l}{f \times 360^\circ} = t_{\text{TOF}} - \frac{\phi_{a,\text{offset}} - \phi_{b,\text{offset}}}{f \times 360^\circ}.$$

Therefore, by plotting the scatter graph of $t_{\text{TOF}} - \Delta\phi$ and performing linear fitting, the values of l and $\phi_{b,\text{offset}} - \phi_{a,\text{offset}}$ can be obtained.

The scatter plot consists of points from each measurement that obeyed the following conditions:

1. The TOF energy measurements are reliable.

For BPMs far from the end of the linac, TOF energy measurements may become unreliable because the bunch is significantly lengthened. In this case, BPM pairs closer to TOF-BPMs, with relative positions and phase offsets that have already been calibrated, can be utilized as TOF devices.

Cavity ϕ_{in} and Voltage Coefficient For each cavity, once the relative position and phase offset between the nearest pair of downstream BPMs are known, they can be utilized in the analysis of forward phase scan data to determine the incoming beam energy ϕ_{in} and the voltage coefficient. This is a common procedure in conventional phase scans, where the cavity model is used to calculate the output energy, and unknown quantities are fitted such that the calculated curve matches the measured ϕ_{set} vs $(\phi_b - \phi_a)$ curve. The fitting is even simpler in this case because the incoming energy is known from TOF measurements at zero cavity voltage as part of the backward voltage scan. Therefore, only ϕ_{in} and voltage coefficient must be determined.

Cavity Positions Once ϕ_{in} and the voltage coefficient for a cavity are known, the distance between the cavity and the BPM unit downstream can be obtained by following the same principle as in Section III.C.1. However, this situation is more complex because the TOF within the cavity must be considered.

Based on the calibration setup illustrated in Fig. 1 [Figure 1: see original paper]:

$$\phi' = \phi - \phi_{\text{out}} + \phi_{\text{in}} - n \times 360^\circ,$$

where ϕ is the phase reading of the BPM; and ϕ_{in} and ϕ_{out} are the phases at the cavity entrance and exit, respectively.

The cavity entrance and exit were chosen such that the cavity fields were effectively zero at these positions. With ϕ_{in} and the cavity voltage coefficient known from the previous step and the incoming beam energy known from TOF measurements, ϕ_{out} can be calculated using beam simulations with the cavity field map.

After leaving the electromagnetic field of the cavity, the particles drift uniformly until they reach the BPM, exhibiting a relationship similar to Eq. (6). Therefore, plotting the scatter graph of $t_{\text{TOF}} - \phi'$ and conducting linear fitting enables determination of the slope as $lf/l_{\text{TOF}} \times 360^\circ$. A simple conversion yields length l.

Cavity Phase Offsets The position calculations in Sections III C 1 and III C 3 enable construction of a lattice model by following the steps illustrated in Fig. 2 [Figure 2: see original paper]. Finally, the relative phase offsets of the cavities and BPMs were obtained. In the previous analysis, the entrance phase ϕ_{in} and cavity voltage of each cavity have already been acquired, as well as the relative positions of all cavities and BPMs. As discussed in Section III C 4, an accurate lattice model can then be constructed, starting from the entrance of the first cavity, where beam simulations can be conducted to determine the time required to travel from the entrance of the first cavity to those of every cavity and BPM. Although $\phi^{(1)}_{\text{RF-ref}}$ in the first cavity is unknown, Eq. (1) and the known set value of the low-level phase ϕ_{set} can be used to compute the relative phase offset ($\phi_{\text{offset}} + \phi^{(1)}_{\text{RF-ref}}$) for each cavity. Similarly, by calibrating all BPM positions, the simulated arrival time can be compared with actual BPM readings to derive the relative phase offsets of BPMs.

Reference Point and Automatic Phase-Setting

The TOF experiment and data analysis provided the relative phase offsets and positions of all cavities and BPMs in the linac. The absolute position of such a section is still unknown and determines the absolute phase offset of each element with the RF reference line.

In hadron linacs, the cavities with phases that must be set are commonly preceded by a radiofrequency quadrupole (RFQ). The beam is bunched out of the RFQ, and its energy does not change during medium-energy beam transport (MEBT), which connects the RFQ to the first cavity. Depending on whether the normally conducting structure upstream can vary its outgoing beam energy, there are two solutions to implement automatic phase-setting.

Fully Model-Based Phase-Setting If the incoming energy to the superconducting section can be varied and there are warm BPMs upstream of the linac, measurements can be taken at several energy values, and techniques similar to those used in the calibration experiment can be used to obtain the distances between the warm elements and the first cold BPM. As the absolute positions of normal-conducting structures and warm BPMs are known to be highly accurate based on mechanical alignment, this final calibration fixes the absolute position of the entire superconducting section.

The reference location where $\phi_{\text{RF-ref}}$ is considered zero is normally placed at the RFQ exit. With their absolute positions known, the absolute phase offsets of all cavities and BPMs can be determined by calculating $\phi_{\text{RF-ref}}$ of the first cavity during the TOF experiment and applying Eq. (1). Therefore, given the beam conditions and lattice design, the required cavity phase settings can be obtained directly via fully model-based calculations.

First Cavity Phase Scan If the accelerating structure directly upstream of the superconducting section is an RFQ, which is an increasingly common layout in modern hadron linacs [34], then adjusting the beam energy at the RFQ exit in a single-beam experiment may be inconvenient. In this case, automatic phase-setting must be achieved in the absence of an absolute position and phase offset of the first cavity. This can be achieved using a conventional phase scan of the first cavity in each run. With E_{in} and E_{out} being measurable from the calibrated

BPMs and the known voltage coefficient, it is simple to determine ϕ_{in} of the first cavity from the phase scan. Subsequently, it is possible to place the phase reference point in the first cavity and use the relative phase offsets between the other cavities and the first cavity to complete the automatic phase-setting.

Experimental Verification of CAFe II

CAFe II Accelerator

The China Accelerator Facility for Superheavy Elements (CAFe II) is a superconducting heavy-ion linac located at the Institute of Modern Physics (IMP). As a modification of the CiADS demonstration facility [35], the main mission of CAFe II is the synthesis of superheavy elements. CAFe II can accelerate heavy-ion beams with charge-to-mass ratios from approximately 1/3 to 4–6.5 MeV/u. Designed for continuous-wave (CW) operation, the average particle current of the beam ranges from 1 to 10 µA.

The superconducting section of CAFe II consists of four CMs. Within each CM, there is a BPM between each pair of adjacent cavities. The first three CMs contain six cavities and five BPMs, whereas the last CM contains five cavities and four BPMs. A schematic of CAFe II is shown in Fig. 3 [Figure 3: see original paper]; the cavity and BPM names are listed in Table 3 . Cavities are named by both the CM to which they belong and their position within it; for example, CM1-3 denotes the third cavity in the first CM.

TOF Alignment and Calibration Experiment

The TOF alignment and calibration experiment at CAFe II followed the procedure detailed in Section III B. After the forward phase scan, a 0.3 mA proton beam was accelerated by 22 superconducting cavities from 1.36 MeV at the RFQ exit to 17.78 MeV at the end of the superconducting linac.

BPM25 and BPM26 after CM4, at the end of the linac, were used as energy measurement devices. These two BPMs were connected to an oscilloscope instead of an electronic system, which allowed observation of the waveform when the beam passed through them. With errors caused by cable transmission calibrated and corrected in advance, manually aligning the two waveforms of BPM25 and BPM26 provided the absolute TOF of the beam from BPM25 to BPM26.

TOF energy measurements from BPM25 and BPM26 were then used to calibrate the distances between the 19 pairs of BPMs, as well as the distances between each BPM and the preceding cavity. As discussed in Section III D, because the CAFe II superconducting section is directly downstream of the RFQ, the calibration ultimately provides the relative positions of all cavities and BPMs, as well as their relative phase offsets.

It is also necessary to discuss experimental details of BPMs. To perform data analysis, the frequency of the BPM unit must be known, as shown in Eq. (6). At a frequency of 162.5 MHz, which is the working frequency of CAFe II, the phase readings of BPMs were susceptible to interference from the electromagnetic field in the cavity. To mitigate this interference, BPM readings were measured at the experimental second harmonic frequency of 325 MHz.

To minimize errors owing to beam fluctuations, 50 samples of BPM readings were taken and the median value was selected. In cases of excessive variance, the dataset was excluded. The findings of the calibration experiment are presented subsequently.

Alignment and Calibration Results

The alignment and calibration results were obtained based on the data analysis scheme described in Section III C. First, the spacing between BPMs was calculated. Fig. 4(a) [Figure 4: see original paper] shows a scatter plot of $t_{\mathrm{TOF}} - \Delta\phi$ for BPM11 and BPM12 at various energies. As the range of BPM readings was between 0–360° [36, 37], making the range $\Delta\phi \pm 360°$, direct linear fitting was not feasible. Therefore, $\Delta\phi$ was adjusted by appropriate increments or decrements of 360° such that all data points could be fitted to a straight line.

The slope and error of the fitting shown in Fig. 4(b) were determined as 122.01 ± 0.04. By multiplying the slope by $l_{\mathrm{TOF}}/(f \times 360°)$, the distance between BPM11 and BPM12 was 639.4 ± 0.2 mm.

Next, the data from the forward phase scan were analyzed using the relative BPM positions. The electromagnetic field distributions of the HWR010 and HWR019 cavities were obtained using CST Studio software [38], and particle transmission through the cavity was performed using TraceWin software [39], which provided the beam simulation code. The cavity voltage coefficient and ϕ_{in} in each cavity were determined as in conventional phase scans.

These results enabled determination of the distance between each cavity and the downstream BPM. Fig. 5 [Figure 5: see original paper] shows a scatter plot of $t_{\mathrm{TOF}} - \phi'$ for CM2-1 and BPM11. The determined values of the fitted slope and error were 19.68 ± 0.15. By multiplying the slope by $l_{\mathrm{TOF}}/(f \times 360°)$, a distance of 103.2 ± 0.8 mm between the CM2-1 cavity exit and BPM11 was obtained. When the spacing between BPMs and the distance between the cavity and BPM are known, the respective positions can be determined.

Fig. 6 [Figure 6: see original paper] shows the TOF-aligned positions of one section of the CAFe II linac as well as the differences between TOF-aligned positions and their respective values in the original lattice design for all cavities and BPMs. Almost all differences in position were smaller than the typical displacements within CMs discussed in Section II B, which shows that TOF alignment results are consistent with the lattice design.

Eight months before this experiment, a TOF experiment that calibrated only BPMs was also conducted. Fig. 7 [Figure 7: see original paper] illustrates the differences between the results of the two calibration experiments. While there were modifications in the low-level RF system between 2022.05 and 2023.01, which caused changes in some relative phase offsets, the relative phase offsets between BPMs unaffected by such modifications remained almost unchanged. These results corroborate the proposition that as long as the positions of cavities and BPMs are fixed and the RF circuit structure remains unchanged, the phase offsets obtained from the calibration experiment remain constant.

Automatic Phase-Setting

To demonstrate automatic phase-setting and verify the calibration results, several new lattice designs were created and the predicted final energies were compared with TOF energy measurements.

In each lattice design, z_{cav} from the alignment results enabled $\phi_{\text{RF-ref}}$ and ϕ_{in} to be calculated via simulations. These two phases, combined with the phase calibration results ϕ_{offset} (which were constant as long as the low-level circuits remained unchanged), allowed ϕ_{set} to be calculated using Eq. (1). Similar to previous data analysis, all simulations were performed using TraceWin. Calculating ϕ_{set} for a CAFe II lattice design required only several minutes, which represented a significant time saving compared to that required for phase scans. Hence, this method can significantly expedite beam tune-up.

Furthermore, any design calculation is expected to have the same level of accuracy regardless of beam intensity. However, this is not the case for cavity phase scans, which suffer from larger errors owing to weaker BPM signals when beam intensity is low. Such errors would pose significant problems for cavity phase scans in the tune-up of heavy-ion beams, which typically have low intensities compared to protons. With automatic phase-setting, low-intensity beams can achieve highly accurate phase-setting as long as the TOF alignment and phase calibration experiments are performed using a high-intensity beam, which is the case for CAFe II.

To examine the accuracy of phase calculations, a new set of lattice settings were constructed by introducing random variations in cavity voltage and synchronous phase based on the original lattice. Owing to a malfunction in BPM21, the new lattice terminated at CM3-6 with a designed exit energy of 9.289 MeV. The operational phase of the cavity was calculated using the previously described method. Subsequently, the TOF of the beam at the CM3-6 exit was measured as 14.65 ns, corresponding to an energy of 9.285 MeV, which closely matched the design value.

Next, the case in which $\phi_{\text{RF-ref}}$ changes in the first cavity was tested. This occurs when the particle type is changed to a particle other than a proton or when there are changes in the RFQ exit energy or the initial phase of the RFQ. To resolve this issue, a phase scan of CM1-1 was performed and the technique discussed in Section III D was applied. Fig. 8 [Figure 8: see original paper] shows the results for a beam tune-up using $^{54}\text{Cr}^{17+}$, where the predicted output energy at each cavity closely agreed with direct TOF energy measurements. These results confirmed the accuracy of the calibration results and validated the effectiveness of automatic phase-setting.

Conclusion

This study proposed a method that employs systematic TOF experiments to calibrate both the positions and phase offsets of cavities and BPMs in a superconducting hadron linac. The method was verified on CAFe II, where calibration results were utilized to achieve rapid automatic phase-setting, and the predicted final beam energies matched direct energy measurements. Its success with CAFe II proves that TOF alignment can resolve the problem of element position shifts within CMs during cool-down, thereby providing a beam-based alternative solution to the more expensive setup of CMs with online alignment capabilities.

After position and phase calibration were conducted on CAFe II, automatic phase-setting replaced the phase scan as the default procedure for beam tune-up and generally accomplished cavity phase and voltage settings within 10 min. This achievement facilitated beam operation at CAFe II with various particle types, including $^{54}\mathrm{Cr}^{17+}$, $^{54}\mathrm{Cr}^{18+}$, $^{40}\mathrm{Ar}^{12+}$, H^{+}, and $^{48}\mathrm{Ca}^{14+}$. The calibration results remained effective over months of operation and are expected to continue holding as long as cavity positions and circuit structures remain unchanged.

Future research should incorporate the acceleration effects of transverse beam offsets into model calculations to improve the accuracy of calibration data analysis and automatic phase setting. The optimal application of position and phase calibration via TOF in long hadron linacs should also be investigated, including the upcoming commissioning of the linac sections of CiADS [40] and HIAF [41], which are two ongoing large-scale accelerator projects under the auspices of IMP. While the calibration principle remains the same as in short linacs such as CAFe II, long linacs may require multiple installations of absolute TOF measurement devices so that the linac can be calibrated in several separate sections. Understanding the effectiveness of different arrangements will aid linac tune-up at CiADS and HIAF and expand the applicability of TOF alignment and calibration in hadron linacs.

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