

On-line measurement of beam phase and energy gain based on beam-cavity interaction

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On-line monitoring of beam phase and energy gain in the cavity is of great importance for the stable operation of accelerators, especially in high-power scenarios. As cavities are typically calibrated with a low-current, short-pulse beam for safety purposes, the beam behavior may deviate from the calibrated case when running high-current beams, due to the strong space charge effect and other possible factors. Motivated by the high-power operation demand at European Spallation Source and the further understanding of beam-cavity interaction, methods for beam phase and energy gain on-line measurement have been developed. The beam phase was measured based on the steady-state cavity model, as demonstrated in the half wave resonator cavity at CAFE2. In this paper, this method was not only applied to a single-cell buncher cavity but also, for the first time, extended to the more complex low-energy multicell RFQ cavity for verification. Additionally, an energy-conservation-based method for measuring beam energy gain in a cavity was proposed and validated.

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I. INTRODUCTION

The European Spallation Source (ESS) [1] is a long pulse neutron source driven by a 5 MW proton linac. It is designed to be the world's brightest neutron source and consists of a normal conducting linac (NCL) followed by a superconducting linac (SCL). The layout is shown in Fig. 1 [2], the NCL comprises an ion source (ISRC), a low-energy beam transport (LEBT), a radio-frequency quadrupole (RFQ), a medium-energy beam transport (MEBT), and a drift-tube linac (DTL). The SCL comprises spoke cavities, medium- β elliptical cavities, high- β elliptical cavities, a high-energy beam transport (HEBT), a dump, and a target. The linac features a high peak current of 62.5 mA and long pulse length of 2.86 ms with a repetition rate of 14 Hz. The ultimate high-level design parameters are shown in Table I [1]. The installation and beam commissioning have been conducted in several steps so far [2–6]. The beam energy will be limited to 800 MeV during the initial operations due

to a budget issue. This will reduce the beam power to 2 MW, and several cryomodules marked with the gray color in Fig. 1 [2] will not be powered during the initial operations. During the last beam commissioning in 2023 [6], a 50 μ s pulse of the nominal 62.5 mA beam current reached the end of DTL4.

For an accelerator which transports such a high-power beam, the measurement of beam phase and energy gain in the cavity is very important. Beam phase is the rf phase experienced by the beam as it passes through the cavity, and energy gain is the energy absorbed by the beam during this process. Both parameters are key indicators of beam-cavity interaction. The measurements of them not only help us to monitor the beam status in the cavity but also provide a potential reference for cross-calibrating key cavity parameters, such as cavity amplitude, cavity phase, and R/Q . As observed during the commissioning, the RFQ output phase has a strong dependency on the beam current [6]. This dependence basically results from deviations of the dynamical behavior of the beam at different beam currents. The on-line monitoring of beam phase and energy gain in the cavity can help us to identify these deviations and subsequently enable us to adjust the cavity to more appropriate operating points.

A variety of methods have been developed to calibrate the beam phase, such as the Delta T phase scan [7], the signature matching phase scan [8], and other methods [9–11]. The calibration based on a phase scan process

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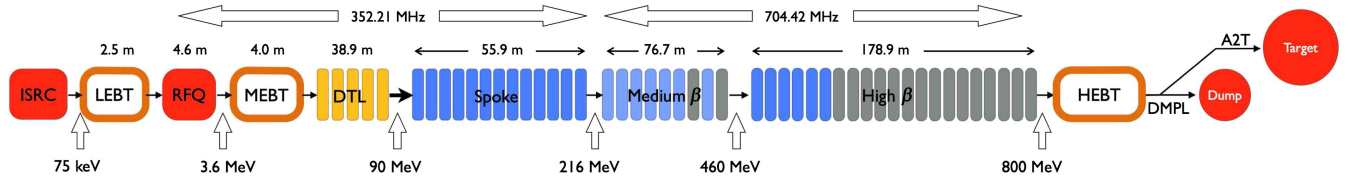


FIG. 1. ESS linac schematic layout for the initial operations with 800 MeV and 2 MW. The segments in the DTL and SC sections denote a DTL tank or a cryomodule. The cryomodules marked with the gray color will not be powered during the initial 2 MW operations.

offers high precision, but it is always a time-consuming offline procedure and is limited by the number and position of the beam position monitor (BPM). Methods based on the measurement of second harmonic of beam signal [12–18] and the measurement of beam-induced higher-order modes (HOM) [19–25] have also been developed. They can achieve on-line monitoring of beam phase without interrupting the operation of beam. However, the second-harmonic-based method relies on phase probes or BPMs to capture the beam signal and inevitably involves a frequency filtering process. Meanwhile, the HOM-based method assumes a cylindrical cavity symmetry and requires specialized HOM couplers, which are not installed in the ESS cavities, to extract the necessary information. Another approach, the beam-transient-based method, has been proposed at DESY [26–29]. This method determines the beam phase by measuring the cavity field change induced by the beam. It enables on-line monitoring of the beam phase using only cavity signals, eliminating the need for extra special probes. However, as the cavity field change is not very significant when the cavity runs with feedback, and maybe unmeasurable if the cavity operates with adaptive feedforward, especially when the beam current is not high enough, the accuracy of this method is limited. Similarly, a method based on the cavity steady-state model has also been achieved in the half wave resonator (HWR) cavity at China Accelerator Facility for superheavy Elements (CAFE2) [30,31]. It focuses on the change of forward voltage when beam passes through the cavity, promising improved accuracy when the cavity runs in closed loop, especially when the beam pulse is sufficiently long.

TABLE I. ESS linac high-level parameters.

Parameter	Unit	Value
Beam power	MW	5
Beam energy	GeV	2
Peak beam current	mA	62.5
Beam pulse length	ms	2.86
Beam pulse repetition rate	Hz	14
Duty factor	%	4
Frequency	MHz	352.21/704.42
Availability	%	95

Although there are many well-established methods for absolute beam energy measurement, such as the measurement using a semiconductor detector [32], the noninterceptive time-of-flight method [33], and others [34–36], the direct measurement of beam energy gain within a cavity remains underdeveloped for proton linacs. However, from the cavity’s perspective, it is the beam energy gain, rather than the absolute beam energy, that directly reflects the cavity state. Therefore, the on-line measurement of beam energy gain offers a more direct and effective means of monitoring cavity status during operation.

Motivated by the high-current and long-pulse operation demands at ESS and the further understanding of beam-cavity interaction, the study of on-line measurement of beam phase and energy gain was conducted at ESS and is presented in this paper. The method used in CAFE2 was adopted to measure the beam phase not only in the buncher cavity but also in the RFQ, where the beam effective phase was calculated to verify the measurement results. In addition, a method for measuring the energy gain based on energy conservation in the cavity was proposed, and it was also validated in both the buncher cavity and the RFQ. The structure of the paper is as follows: the principles of the methods are specifically introduced in Sec. II. In Sec. III, the measurement results obtained from two methods are cross verified based on the data collected from ESS Buncher2. In Sec. IV, the measurement results at ESS RFQ are also validated by theoretical calculations. Finally, we summarize the paper in Sec. V.

II. MEASUREMENT METHODS

A. Beam phase measurement based on the cavity model

In accelerator physics, the beam phase ϕ_b is defined as the angle between the beam current vector $\mathbf{I}_b$ with respect to the cavity voltage $\mathbf{V}_c$ [37]. If the cavity is well tuned and the cavity detuning caused by the external perturbation is negligible, the beam phase can be represented by the angle between the beam-induced voltage $\mathbf{V}_b$ with respect to the cavity voltage $\mathbf{V}_c$, as the directions of $\mathbf{I}_b$ and $\mathbf{V}_b$ will align in this case. Then the key to measuring the beam phase is the determination of the beam-induced voltage $\mathbf{V}_b$.

By Implementing the cavity model given in [37,38], the beam-induced voltage can be calculated from the cavity state equation [30,31]:

$$\frac{d\mathbf{V}_{c,b}(t)}{dt} + \omega_{1/2}\mathbf{V}_{c,b}(t) = 2\frac{\beta\omega_{1/2}}{1+\beta}\mathbf{V}_{f,b}(t) + \omega_{1/2}\mathbf{V}_b, \quad (1)$$

where $\omega_{1/2}$ is the half bandwidth of the cavity, β is the coupling coefficient between the cavity and the power source, and $\mathbf{V}_f$ is the forward voltage. The second subscript indicates the presence of the beam: b means beam present, and nb means no beam. To improve the accuracy of the measurement, it is necessary to correct Eq. (1) with the cavity state equation in the absence of beam:

$$\frac{d\mathbf{V}_{c,nb}(t)}{dt} + \omega_{1/2}\mathbf{V}_{c,nb}(t) = 2\frac{\beta\omega_{1/2}}{1+\beta}\mathbf{V}_{f,nb}(t), \quad (2)$$

so that the influence of factors other than the beam on cavity voltage and forward voltage can be eliminated. After the correction, the cavity state equation can be expressed as

$$\frac{d\Delta\mathbf{V}_c}{dt} + \omega_{1/2}\Delta\mathbf{V}_c(t) = 2\frac{\beta\omega_{1/2}}{1+\beta}\Delta\mathbf{V}_f(t) + \omega_{1/2}\mathbf{V}_b, \quad (3)$$

where $\Delta\mathbf{V}_c = \mathbf{V}_{c,b} - \mathbf{V}_{c,nb}$ and $\Delta\mathbf{V}_f = \mathbf{V}_{f,b} - \mathbf{V}_{f,nb}$.

For specific operating modes of the cavity, Eq. (3) can be simplified accordingly. When the cavity runs in open loop, the forward voltage will be almost stable, and $\Delta\mathbf{V}_f$ will be negligible. Then the relation between $\mathbf{V}_b$ and $\mathbf{V}_c$ can be expressed as

$$\frac{d\Delta\mathbf{V}_c}{dt} + \omega_{1/2}\Delta\mathbf{V}_c(t) = \omega_{1/2}\mathbf{V}_b, \quad (4)$$

which shows that $\mathbf{V}_b$ can be determined by measuring the change of cavity voltage when beam passes through.

Besides being applied for open-loop operation, Eq. (4) can also be used in closed-loop feedback-only operation [28], where the beam transient still exists because of the delay of the feedback, but it is not very significant. Actually, for a cavity that runs in closed loop, the change of forward voltage is more suitable to be used for the beam-induced voltage calculation [30], especially when the beam pulse is long. When the cavity runs in closed loop, the influence of transient beam loading on the cavity voltage will be almost canceled by a well-designed feedback or adaptive feed-forward control. Thus, $\Delta\mathbf{V}_c$ will be nearly negligible in Eq. (3), therefore the change in the forward voltage $\Delta\mathbf{V}_f$ should be considered instead. Then we can have the beam-induced voltage by measuring the change of the forward voltage as the beam passes through the cavity [30,31]:

$$\mathbf{V}_b = \frac{2\beta}{1+\beta}(\mathbf{V}_{f,nb} - \mathbf{V}_{f,b}). \quad (5)$$

After the beam-induced voltage is measured, the beam phase can be derived by calculating the angle between the

induced voltage and the cavity voltage according to the definition in [31]:

$$\phi_b = \pi - \angle(\mathbf{V}_b, \mathbf{V}_c). \quad (6)$$

B. Energy gain measurement based on energy conservation

The method proposed for beam energy gain measurement is based on the energy conservation in the cavity. Specifically, in closed-loop operation, the power fed into the cavity is distributed among three components: the first part is transferred to the beam as energy gain, the second part is dissipated as heat due to the surface resistance of the cavity walls, and the third part corresponds to the change rate of the cavity stored energy. The energy conservation can be expressed as

$$P_{in,b} = P_b + P_{diss,b} + \left(\frac{dW}{dt}\right)_b, \quad (7)$$

where P_{in} is the power fed into the cavity, which can be measured from the difference between the forward power P_f and the reflected power P_r : $P_{in} = P_f - P_r$, P_b is the power absorbed by the beam, P_{diss} is the dissipated power, which is determined by the cavity voltage V_c and shunt impedance R_{sh} with a relation: $P_{diss} = \frac{V_c^2}{R_{sh}}$, W is the cavity stored energy, which is determined by the dissipated power P_{diss} , cavity resonance frequency ω_0 , and the unloaded quality factor Q_0 at ω_0 of the cavity, with the relation: $W = \frac{Q_0 P_{diss}}{\omega_0}$. Generally speaking, when the cavity runs in closed loop, the cavity voltage will be kept almost constant by the feedback control as mentioned above. In this case, the dissipated power P_{diss} and the cavity stored energy W will not vary with the presence of the beam. Then the energy conservation in the absence of beam can be written as

$$P_{in,nb} = P_{diss,nb} + \left(\frac{dW}{dt}\right)_{nb} = P_{diss,b} + \left(\frac{dW}{dt}\right)_b. \quad (8)$$

By comparing Eqs. (7) and (8), the power absorbed by the beam can be expressed as

$$P_b = P_{in,b} - P_{in,nb} = P_{f,b} - P_{r,b} - (P_{f,nb} - P_{r,nb}). \quad (9)$$

So basically, by measuring the changes of forward power and reflected power when beam passes through the cavity, the power absorbed by the beam can be deduced.

At the same time, once the beam-induced voltage $\mathbf{V}_b$ is measured from Eq. (5), the beam current can be deduced through:

$$I = \frac{|\mathbf{V}_b|}{(R/Q)Q_L}, \quad (10)$$

where R/Q is the characteristic impedance, and Q_L is the loaded quality factor of the cavity. Alternatively, the beam current I can also be measured by a beam current monitor, if one is available in reasonable proximity to the cavity. Then, we can calculate the beam energy gain in the cavity through:

$$\Delta W = \frac{P_b}{I}. \quad (11)$$

III. VERIFICATION OF THE MEASUREMENT METHODS FOR A SINGLE-CELL CAVITY

Based on the data collected from the last beam commissioning at the ESS Buncher2 cavity, the reliability of the methods for beam phase and energy gain measurement has been verified for a single-cell cavity.

A. Introduction to the ESS Buncher2 cavity

The ESS Buncher2 cavity is the second buncher cavity in the MEBT of the ESS linac, as shown in Fig. 2 [39]. The main function of this buncher is to achieve longitudinal beam matching, in conjunction with the other two bunchers. The parameters of Buncher2 have been optimized based on the beam dynamics, the main design parameters are shown in Table II.

B. Measurement specifications

During beam commissioning, the rf phases of Buncher2 were scanned in closed-loop operation under various beam conditions. At each rf phase step, the beam phase and energy gain were measured over 60 pulses with the methods introduced in Sec. II. With the effective voltage VT , known to the best of our knowledge, the beam phase and energy gain are related as

$$\Delta W = qVT \cos(\phi_b). \quad (12)$$

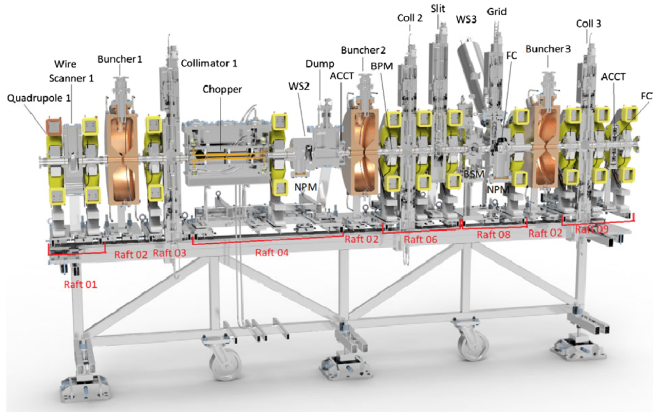


FIG. 2. Schematic of ESS MEBT.

We assumed the effective voltage remained stable during the phase scan, and used Eq. (12) to derive the beam energy gain after measuring the beam phase from the cavity-model-based method. Similarly, after measuring the beam energy gain from the energy-conservation-based method, we also used Eq. (12) to derive the beam phase. Then, by comparing the directly measured results with the derived results at each rf phase step, the reliability of both methods was cross validated.

To measure beam phase and energy gain, the necessary basic data were collected by the LLRF system. A typical set of acquired data is shown in Fig. 3. The corresponding beam current was 20 mA, and the beam pulse length was 50 μ s.

In practice, as there are signal deviations resulting from the signal transmission in the cable, crosstalk, and other degrading effects, the forward and reflected signals should be calibrated as described in Refs. [30,40–44] before being used for the measurement. Here, only the insertion loss of the signal cables has been taken into account in the calibration, as the directional couplers at ESS have excellent directivity (above 40 dB), making the crosstalk between the forward and reflected signals negligible. Figures 4 and 5 show the amplitude and phase of the forward voltage before and after calibration, respectively, clearly demonstrating the observed differences.

For a cavity operating with a pulsed beam, both the data with and without beam can be extracted from the same pulse. To alleviate measurement errors caused by background noise, we averaged the basic parameters over a specific time window, when the waveforms were stable at the stage with and without beam present, respectively. Specifically, in the presented case, the beam arrived at the cavity at approximately 152 μ s, the time window for averaging without beam spanned from 140 to 145 μ s, and the time window for averaging with beam spanned from 195 to 200 μ s.

C. Comparison and analysis of the measurement results

Based on the above specifications, the measurement results at different rf phases are presented. The energy gains

TABLE II. Parameters of ESS Buncher2.

Parameter	Unit	Value
Transit-time factor		0.6488
Effective voltage	kV	59.7
Designed beam phase	$^\circ$	-90
Length	mm	128
Aperture (R)	mm	15
Frequency	MHz	352.21
Coupler factor		1.02
Q_L		8893
R/Q		76.7

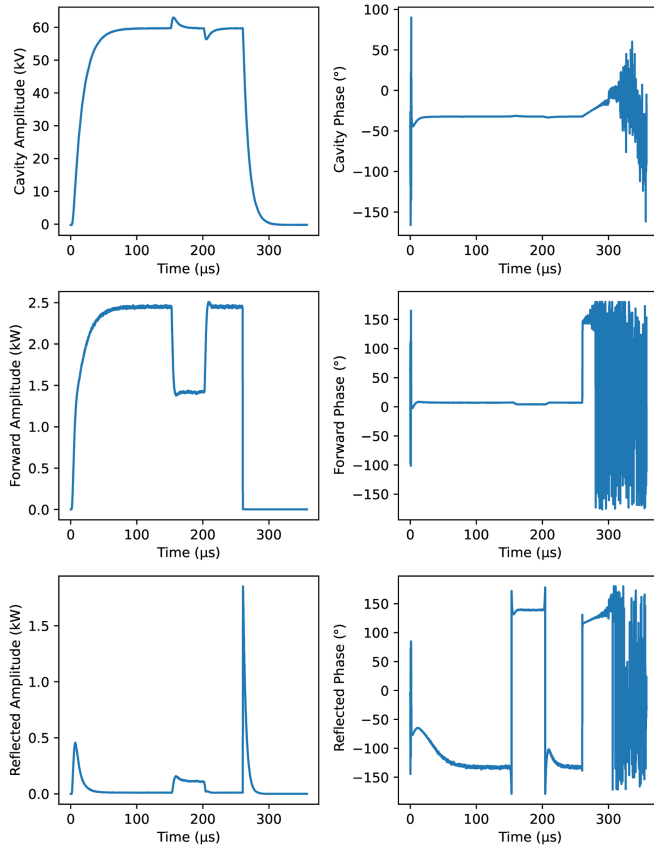


FIG. 3. Basic rf waveform of ESS Buncher2.

directly measured from the energy conservation and those derived from Eq. (12) with the measured beam phases are compared in Fig. 6. The beam phases directly measured from the cavity model and those derived from Eq. (12) with the measured energy gains are compared in Fig. 7. In both figures, the root mean square error (RMSE) between the

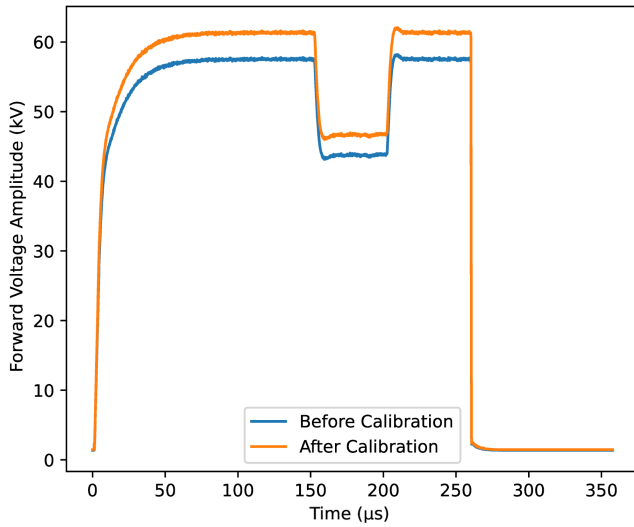


FIG. 4. Forward voltage amplitude before and after calibration.

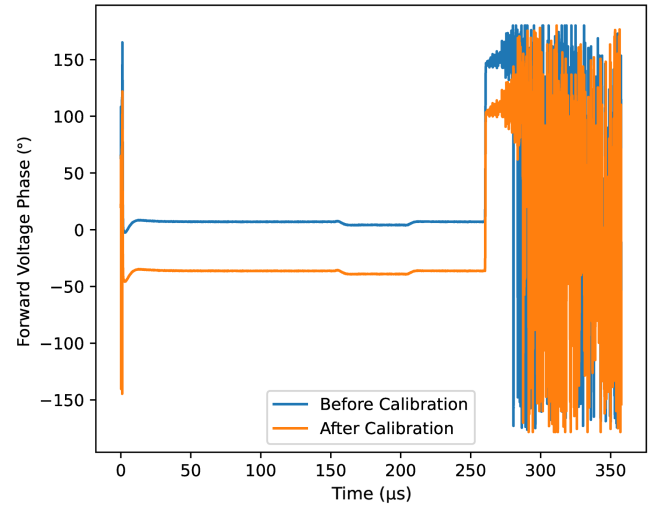


FIG. 5. Forward voltage phase before and after calibration.

directly measured and derived results is presented to show eventual differences between the two sets of results.

As the results demonstrate, there is excellent consistency between the directly measured values and the derived values. The average RMSE over all rf phase steps is 0.28 keV for the energy gain and 0.54° for the beam phase. Furthermore, to validate the measurement results of both methods, the beam phase calibrated by a BPM using the traditional phase scan method [2] is also shown in Fig. 7, marked with a magenta star. Good agreement is observed between the calibration and the measurements.

In Fig. 8, the standard deviations σ of the measured energy gains and measured beam phases over 60 pulses at each rf phase step are presented. The average standard deviations of the measured energy gains and beam phases over all rf phases are 0.13 keV and 0.18° , respectively,

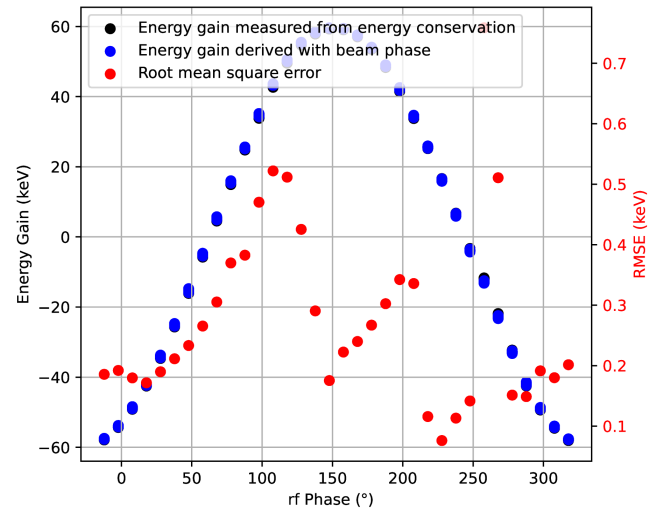


FIG. 6. Comparison between measured and derived energy gain.

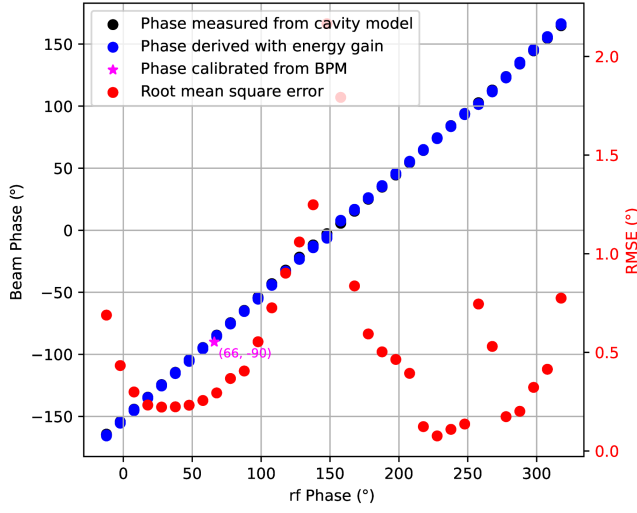


FIG. 7. Comparison between measured and derived beam phase.

demonstrating that the measurement precision is quite high under this beam condition.

The precision of the beam phase and energy gain measurement depends not only on the measurement instruments, which have been improved at ESS with high-performance hardware, but also on the beam conditions, especially the beam current, as both methods introduced in Sec. II are based on the beam-cavity interaction. The results presented above correspond to a beam current of 20 mA. Scenarios at different beam currents have also been analyzed, as shown in Fig. 9, all demonstrating good agreement between the directly measured results and the derived results. The average standard deviations of the measurement results across different beam currents are presented in Fig. 10. As shown, with the increase of the beam current, the average σ of the results tends to get smaller, which means a better precision at higher current.

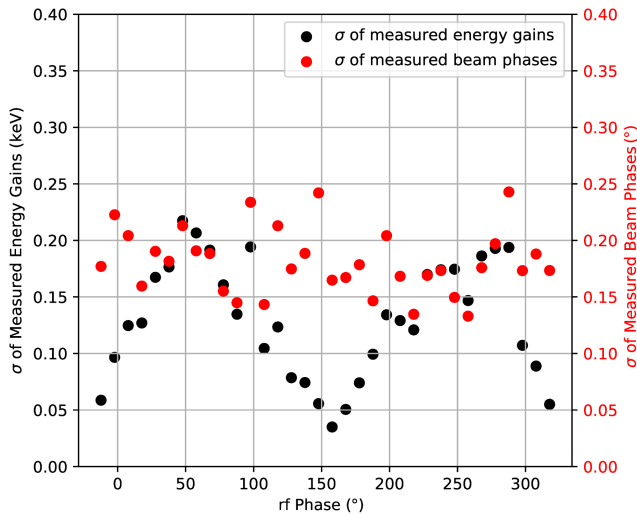


FIG. 8. Standard deviation of measurement results.

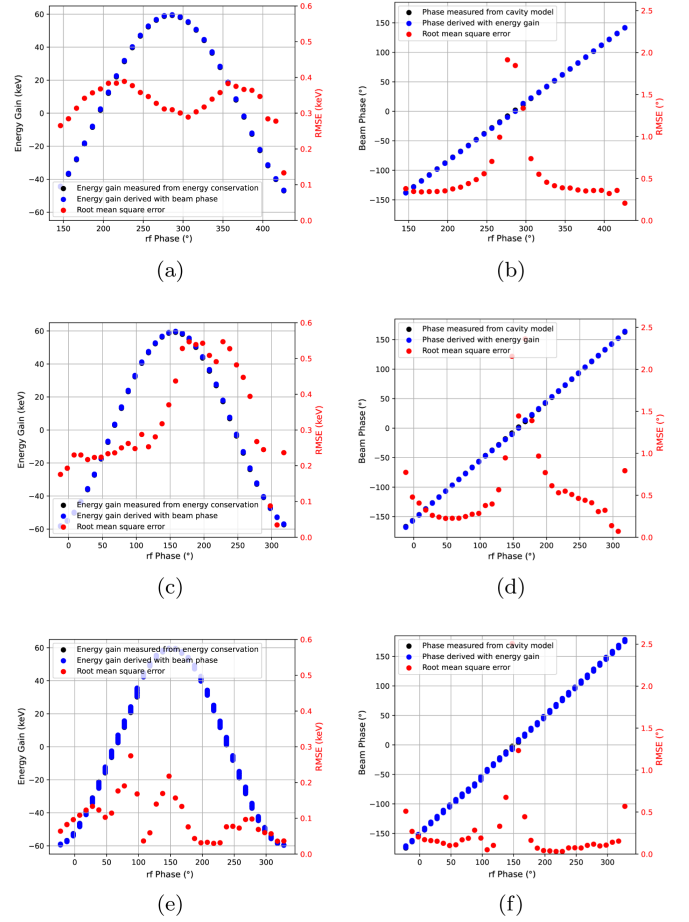


FIG. 9. Comparisons between measured and derived results at different beam currents. (a), (c), and (e) show comparisons of energy gain at 60, 38, and 3 mA, respectively. (b), (d), and (f) show comparisons of beam phase at the same three currents.

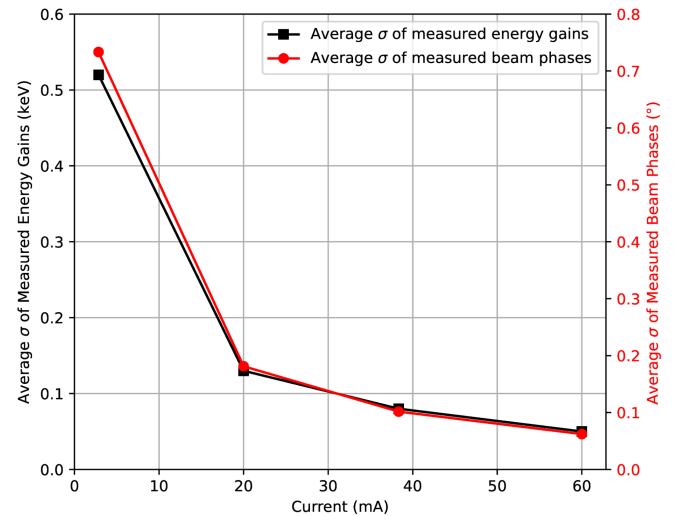


FIG. 10. Average standard deviation of measurement results at different beam currents.

Furthermore, even with beam currents just above approximately 3 mA, the average σ of the energy gain directly measured from the energy-conservation-based method is 0.52 keV, and the average σ of the beam phase directly measured from the cavity-model-based method is 0.73° , the precision is still sufficiently good.

IV. VALIDATION OF THE MEASUREMENT METHODS FOR A MULTICELL CAVITY

Based on the data collected from last beam commissioning at the ESS RFQ cavity, the feasibility of the methods for beam phase and energy gain measurement has also been validated for a multicell cavity.

A. Introduction to the ESS RFQ cavity

The ESS RFQ [45–47] is a high-current RFQ, designed for a beam current up to 70 mA. It accelerates a proton beam from 75 keV to 3.62 MeV in a 4.55 m-long structure. One characteristic of the RFQ is that the intervane voltage varies along its length, starting at 80 kV and increasing to 120 kV at the end. The evolutions of the intervane voltage and synchronous phase are shown in Fig. 11, and the key parameters of the RFQ are presented in Table III.

B. Definitions of effective voltage and effective beam phase

In multicell cavities like the RFQ, focusing on the beam information in each individual cell is complex and can become tedious. Instead, here we are more interested in the overall effect of the cavity electromagnetic field on the beam. Therefore, we introduce the effective voltage $\mathbf{V}_{\text{eff}}$, which is exactly the vector sum $\mathbf{V}_{\text{sum}}$ of the voltages at each cell $\mathbf{V}_n$, and the effective beam phase ϕ_{eff} , which is exactly the phase we can calculate from the cavity model, to describe the overall effect of the cavity on the beam:

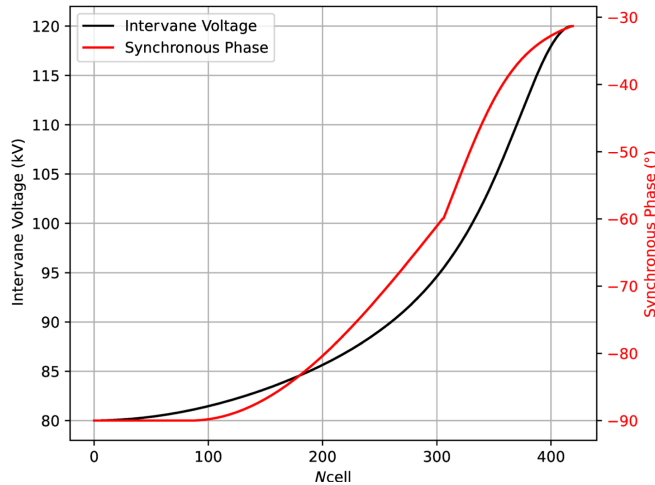


FIG. 11. Evolution of the intervane voltage and synchronous phase of ESS RFQ.

$$\mathbf{V}_{\text{eff}} = \mathbf{V}_{\text{sum}} = \sum_{n=1}^N \mathbf{V}_n, \quad (13)$$

$$\phi_{\text{eff}} = \pi - \angle(\mathbf{V}_b, \mathbf{V}_{\text{eff}}). \quad (14)$$

From the perspective of beam acceleration, the overall effect of the cavity on the beam should be equivalent to the collective effects of all individual cells. Specifically [48], the active power required from the generator to accelerate the beam is determined by the sum of the energy gain from each cell, which brings:

$$P_b = \frac{1}{2} |\mathbf{V}_{\text{eff}}| |\tilde{\mathbf{i}}_b| \cos \phi_{\text{eff}} = I \sum_{n=1}^N V_{zn} T_n \cos \phi_n, \quad (15)$$

where $\tilde{\mathbf{i}}_b$ is the harmonic component of the beam current I at the bunch frequency (in our case, 352 MHz), and V_{zn} , T_n , and ϕ_n are the axial voltage, transient time factor, and beam phase at cell n , respectively. Similarly, the reactive power required from the generator to keep the beam in phase with the accelerating voltage is given by the sum of the cell-by-cell reactive power:

$$Q_b = \frac{1}{2} |\mathbf{V}_{\text{eff}}| |\tilde{\mathbf{i}}_b| \sin \phi_{\text{eff}} = I \sum_{n=1}^N V_{zn} T_n \sin \phi_n. \quad (16)$$

Then we can define the effective beam phase and effective voltage, which summarize the overall rf effect of the acceleration through a multicell cavity [49]:

$$\phi_{\text{eff}} = \arctan \frac{\sum_{n=1}^N V_{zn} T_n \sin \phi_n}{\sum_{n=1}^N V_{zn} T_n \cos \phi_n}, \quad (17)$$

$$|\mathbf{V}_{\text{eff}}| = \frac{\sum_{n=1}^N V_{zn} T_n \cos \phi_n}{\cos \phi_{\text{eff}}}. \quad (18)$$

In the RFQ scenario, the transit-time factors are $\pi/4$, the same in each cell, and the acceleration efficiency A should

TABLE III. Parameters of ESS RFQ.

Parameter	Unit	Value
Frequency	MHz	352.21
Voltage	kV	80–120
Input current	mA	70
Inner length	m	4.545
Input energy	MeV	0.075
Output energy	MeV	3.62
Transmission	%	97
Coupler factor		1.35
Q_L		3361
R/Q		2209

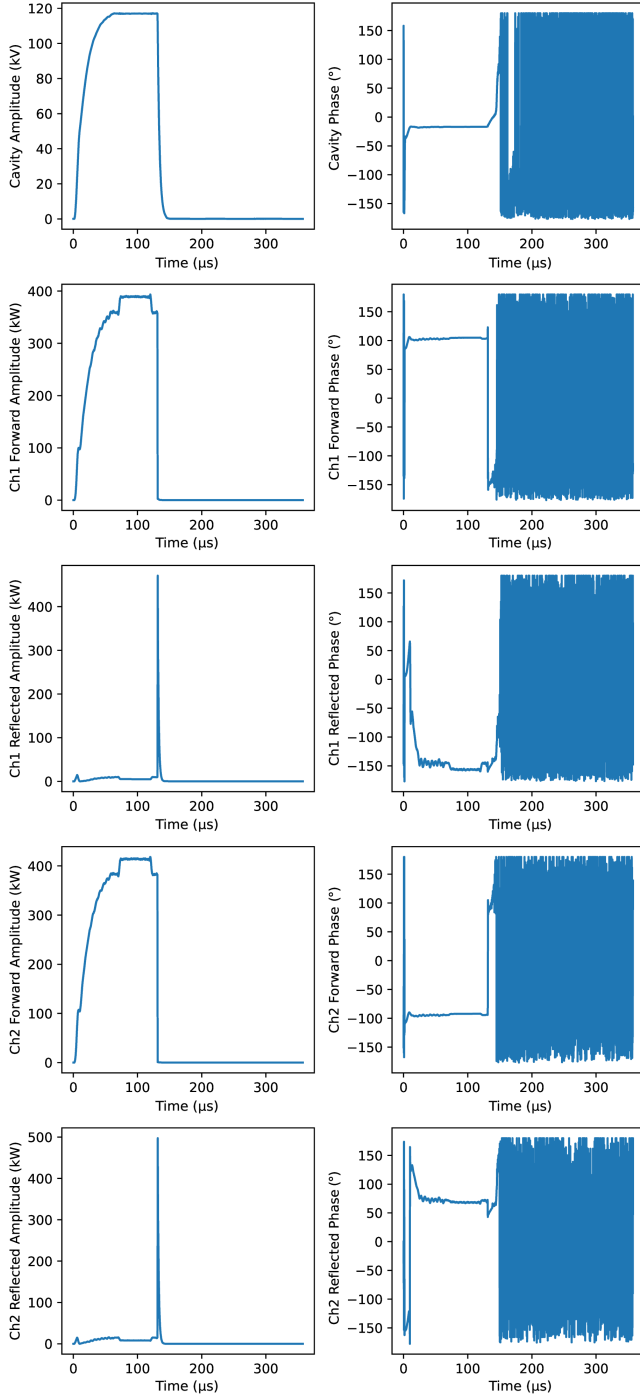


FIG. 12. Basic rf waveform of ESS RFQ.

be considered for its axial voltage $V_{zn} = A_n V_n$ [50], so we have [51]:

$$\phi_{\text{eff}} = \arctan \frac{\sum_{n=1}^N A_n V_n \sin \phi_n}{\sum_{n=1}^N A_n V_n \cos \phi_n}, \quad (19)$$

$$|V_{\text{eff}}| = \frac{\pi}{4 \cos \phi_{\text{eff}}} \sum_{n=1}^N A_n V_n \cos \phi_n. \quad (20)$$

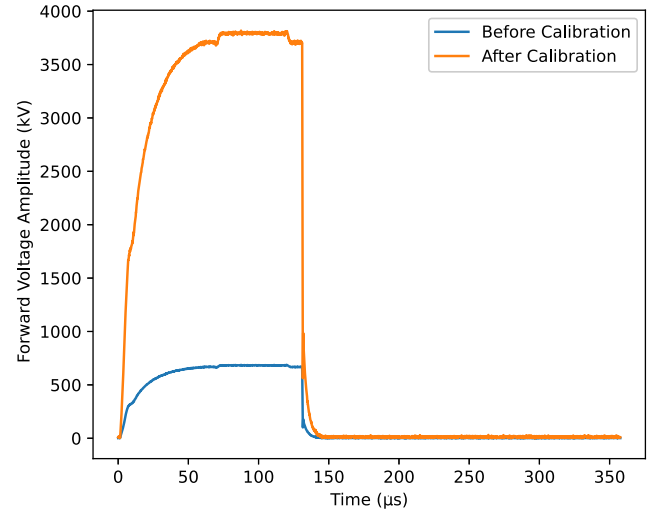


FIG. 13. Summed forward voltage amplitude before and after calibration.

C. Measurement specifications and results

In the RFQ, the effective beam phase can be measured with the cavity-model-based method, and the energy gain can be measured with the energy-conservation-based method. Unlike the single-cell case, where the results of the two methods can be cross verified via the effective voltage, the effective voltage in the RFQ cannot be measured directly. It can be estimated by combining the directly measured cavity voltage with the RFQ beam dynamical parameters according to the definition, but the calculation is complicated and prone to errors due to finite measurement precision. Considering this, the measurement results in the RFQ will be verified with theoretical calculations instead, as described in the following section.

The measurement procedures are similar to those in the buncher. The RFQ cavity was operated in closed loop with adaptive feed forward during the measurements. The corresponding beam current was 20 mA and the beam pulse was 50 μs , consistent with the beam condition in Buncher2 in the previous case. However, different from the buncher, the power to the RFQ at ESS is fed through two channels, and the signals from both channels must be summed before being calibrated and used for the measurements. The basic data collected for the effective beam phase and energy gain measurement are shown in Fig. 12. Figures 13 and 14, respectively, show the amplitude and phase of the summed forward voltage from both channels before and after calibration. The beam arrived at the RFQ cavity at approximately 68 μs , the time window for averaging without beam spanned from 62 to 68 μs , and the time window for averaging with beam spanned from 90 to 110 μs .

With the above specifications, the effective beam phases and energy gains were measured at different RFQ voltages. The results are shown in Fig. 15.

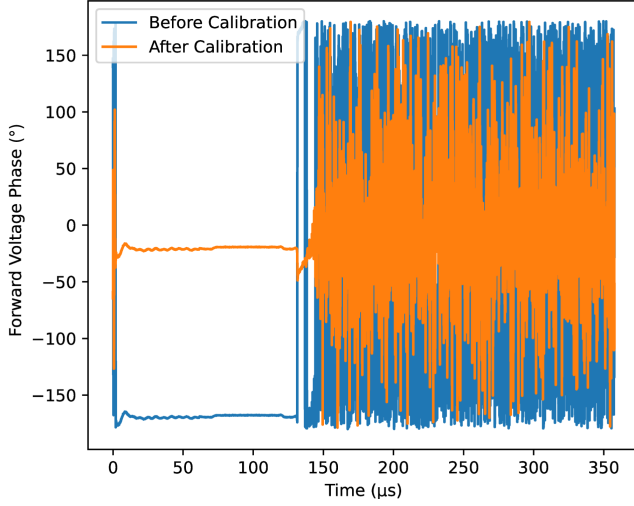


FIG. 14. Summed forward voltage phase before and after calibration.

D. Validation with the theoretical analysis

To verify the measurement results, the RFQ effective beam phases and energy gains at different cavity voltages were calculated based on the analysis of the longitudinal beam dynamics in the RFQ.

In the nominal case, where the beam phase and intervane voltage in each RFQ cell are the same as those in the RFQ dynamical design, the effective beam phase and beam energy gain from the RFQ can be calculated according to the definitions in Sec. IV B. When the cavity voltage deviates from the nominal case, the energy gains and the beam phases in each RFQ cell will also deviate from the designed values. If we look at the details of the beam behavior on a cell-by-cell basis, the deviations of energy gain and beam phase in a particular cell will affect the beam behavior in the following cells. As shown in Fig. 16, $dE^{(m)}$ and $dt^{(m)}$ are defined as the energy gain deviation and time

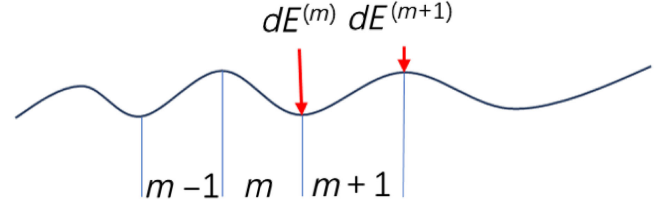


FIG. 16. Schematic of deviations in multicell scenario.

deviation at the end of cell m , the iterations of the energy gain deviation and time deviation from cell to cell should be [52]:

$$dE^{(m+1)} = dE^{(m)} + dU_{rf} + dU_H, \quad (21)$$

$$dt^{(m+1)} = dt^{(m)} + dt_f, \quad (22)$$

where dU_{rf} is the rf error caused by the arrival time error and voltage error in cell $m+1$, dU_H is caused by the HOM effect in cell $m+1$, which is omitted in this work to simplify the calculation. And dt_f is the deviation of the time of flight in cell $m+1$. Furthermore, the energy gain deviation and the time deviation in each RFQ cell are also coupled with each other, following the relationships:

$$\begin{aligned} dU_{rf} &= \frac{e\pi A}{4} V_1 \cos \phi_1 - \frac{e\pi A}{4} V_0 \cos \phi_0 \\ &= \frac{e\pi A}{4} (V_1 \cos(\phi_0 + \omega dt^{(m)}) - V_0 \cos \phi_0), \end{aligned} \quad (23)$$

$$\begin{aligned} dt_f &= \frac{L}{c\sqrt{1-1/\gamma_1^2}} - \frac{L}{c\sqrt{1-1/\gamma_0^2}} \\ &= -\frac{L}{m_0 c^3 (\gamma_0^2 - 1)^{3/2}} dE^{(m+1)}, \end{aligned} \quad (24)$$

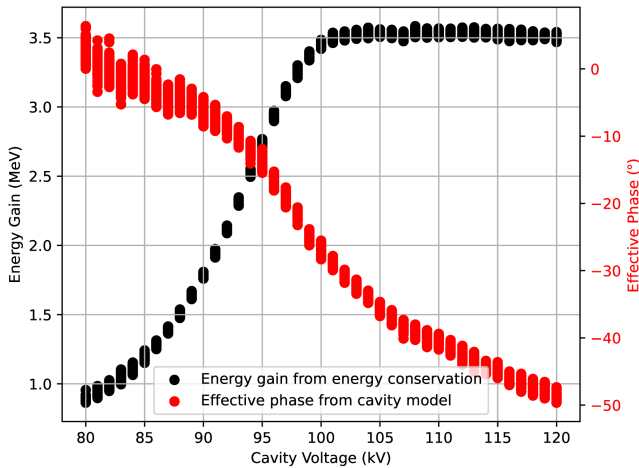


FIG. 15. Effective beam phase and energy gain measurement results.

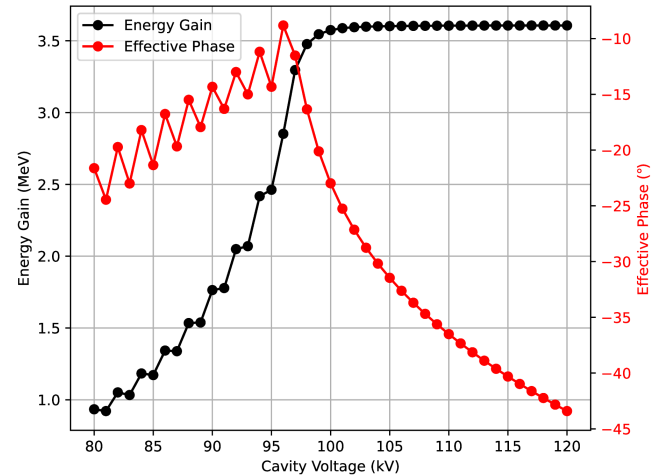


FIG. 17. Effective beam phase and energy gain calculation results.

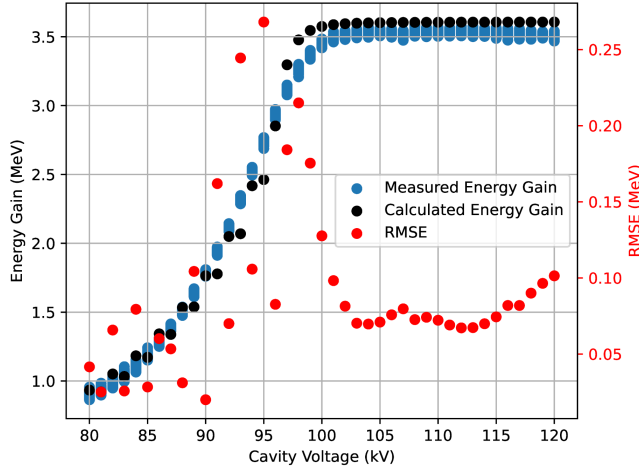


FIG. 18. Energy gain comparison between measurements and calculations.

where V_1 and V_0 are the deviated and nominal voltages in cell $m + 1$, ϕ_1 and ϕ_0 are the beam phases at cell $m + 1$ with and without voltage deviation, respectively. L is the length of cell $m + 1$, γ_1 and γ_0 denote the Lorentz factors corresponding to the particle velocities in cell $m + 1$ with and without voltage deviation, respectively. Based on the above equations, the deviations of energy gain and beam phase in each RFQ cell resulting from voltage deviation can be calculated, and the corresponding effective beam phase and energy gain for the entire RFQ can then be deduced.

In the measurement, the directly measured RFQ cavity voltage was scanned from 120 to 80 kV, in steps of 1 kV. The cavity voltage of 120 kV corresponds to the designed case, where the maximum intervane voltage is exactly 120 kV. In the calculation, the intervane voltages in each RFQ cell were regarded to be scaled by a ratio, when the cavity voltage deviated from the nominal value of 120 kV. For example, when the cavity voltage is 100 kV, the intervane voltage in each RFQ cell will be $V(n) = \frac{100}{120} V_0(n)$, where $V_0(n)$ is the designed voltage at cell n . Based on the beam dynamic analysis above and the ESS RFQ parameters given in Sec. IV A, the effective beam phases and energy gains at different voltages were calculated. The results are shown in Fig. 17.

Figures 18 and 19 compare the energy gains and effective beam phases between measurements and calculations. As demonstrated, when the voltage deviation is within 20 kV, the measured and calculated energy gains show strong agreement, with an RMSE of almost below 0.1 MeV, and the evolution of the measured effective beam phases aligns well with the calculated results, with an RMSE of almost below 5° . As the theoretical calculations are based on the ideal scenario, such differences, and the larger discrepancies observed when the voltage deviates significantly from the design value, are expected.

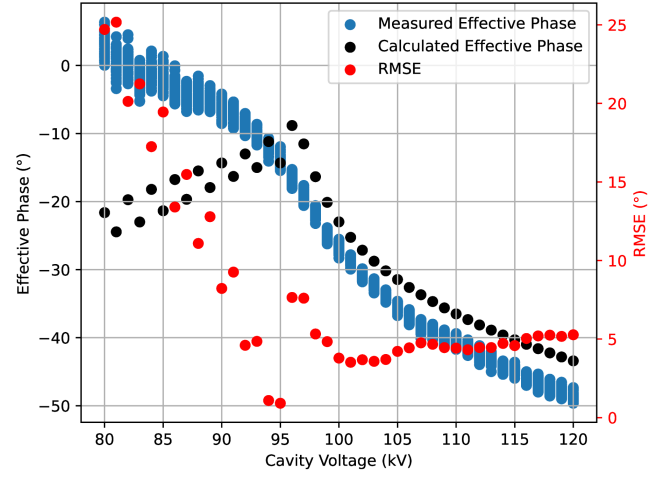


FIG. 19. Beam phase comparison between measurements and calculations.

V. SUMMARY

Motivated by the high-power operation demand at ESS and the further understanding of beam-cavity interaction mechanism, methods based on the cavity model and energy conservation have been developed to achieve the on-line monitoring of beam phase and energy gain in a cavity. The methods were detailed in principle, and verified in both single-cell and multicell cavities, based on the data collected from the last beam commissioning at the ESS Buncher2 and RFQ, respectively. The excellent agreement between the measured and derived results obtained from two methods, with the average RMSE of 0.28 keV for energy gain and 0.54° for beam phase, demonstrates the reliability of the methods for single-cell cavities. Even at a low beam current of 3 mA, the measurements maintained sufficiently high precision, with an average standard deviation of 0.52 keV for energy gain and 0.73° for beam phase. Furthermore, the good agreement between the measurement results and theoretical calculations performed at the ESS RFQ confirms the feasibility of the methods for multicell cavities.

The analysis in this paper was conducted on NC cavities, but the methods can also be extended to SC cavities as effective diagnostics. For further development, the detuning effect should be considered, especially when the cavity is not well tuned. This is particularly important for SC cavities, where significant Lorentz force detuning can occur at high fields. The methods presented in this paper will not only enable real-time monitoring of beam and cavity status, facilitating accelerator fault detection and failure compensation, but also provide a valuable reference for cavity calibration, ensuring optimal cavity performance across varying beam conditions.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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