PHASING SCHEMES FOR THE CEBAF CAVITIES*

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Abstract

The CEBAF accelerator requires accurate phasing of the 338 superconducting cavities to achieve the design rms energy spread of $2.5\cdot10^{-5}$. The rms phase error along each linac, with 160 cavities over a length of 200 m, may not exceed 2.6°, assuming that the whole linac is operated on crest. The common procedure is to maximize the energy gain with a spectrometer. At CEBAF, however, phase-dependent cavity steering effects cause deflections of the beam of several mrad, requiring steering corrections in the linac, which makes this method very time consuming. Beam-induced transients can also be used in pulsed operation to determine the zero-energy-gain phase with high accuracy. Better than 2° accuracy is achieved when the signal-to-noise ratio is improved by signal averaging. These and other approaches for the phasing of cavities are compared and accuracy and feasibility are discussed.

I. PHASE STABILITY REQUIREMENTS

The overall specification for the CEBAF accelerator is given in Table 1.

Table 1: Accelerator Parameters

Energy	E = 0.5-4.0	GeV
Energy spread	$\sigma_E/E \le 2.5\cdot10^{-5}$	at 1 GeV
Beam current	0 – 200	μA

The low energy spread of the beam requires strict amplitude and phase control of the RF field in the superconducting cavities according to table 2.

Table 2: RF amplitude and phase stability requirements with vernier system maintaining linac on crest

	uncorrelated	correlated
σ_A/A: gradient error	$2\cdot10^{-4}$	$1.1\cdot10^{-5}$
σ_f: fast phase error	0.25°	0.13°
σ_s: slow phase error	2.6°	-

The rms phase error along a linac with 160 cavities may not exceed 2.6°. A phase vernier system will maintain the overall phase of the linacs on crest while a gradient vernier [1] system will maintain constant energy at the end of the linac. With the overall phase of the linac being on crest, the individual cavities need to be phased better than ±5.2° to meet the specification in table 2. The goal is to initially phase cavities better than ±2°.

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II. PHASING SCHEMES

During accelerator operation the phase of the accelerating field of individual cavities must be maintained better than ±5.2°. When the RF system is turned on for the first time, the actual accelerating phase is not known, since the electrical length of the probe cables may differ by more than ±180°. The electrical length can be measured with a TDR or network analyzer and be used to calculate the actual phase as described in Section VII. This method is not very accurate, since RF control module internal phase shifts and the geometry of the cavities to calculate the drifttime of the beam have to be taken into account. More accurate are measurements which use the beam as reference. The following phasing methods have been evaluated during north linac operation at typical energies between 100 MeV and 150 MeV with more than 100 superconducting cavities operational:

- Phasing of cavities by maximizing energy with a spectrometer as energy detector.
- Phasing of cavities by minimizing beam–induced transients during pulsed beam operation to determine the phase with zero energy gain.
- Phasing of cavities by measurement of the phase of the beam–induced field with a phase detector in the RF control module.
- Phasing by minimizing residual gradient fluctuations due to beam current modulation to determine the phase with zero energy gain.

In some cases the phase for maximum energy gain (crest phase) is determined directly; in other cases the phase for zero energy gain (zero crossing of the accelerating field) is determined and a 90° offset added or subtracted to set the crest phase.

III. PHASING WITH SPECTROMETER

Cavity phasing with the spectrometer makes use of the dependency between energy gain of the cavity and phase of the accelerating field. The energy gain is maximized using a spectrometer. This method can be automated and computer controlled.

Manual Phasing

For the initial cavity phasing a spectrometer at the end of the north linac was used. Changes in energy were observed on a view screen with a radius of 17.5 mm corresponding to an energy change of ≈1% at an energy of 100 MeV. In the spreader region at a location with a dispersion of 1.1 m, a position resolution of 0.1 mm corresponding to an energy change of $1 \cdot 10^{-4}$ can be detected. At a field gradient of 5 MV/m the achieved phase resolution is

$$\phi = \cos^{-1}\left(1 - \frac{\Delta E}{E_0} \cdot \frac{E_0}{E_{acc} / 2}\right) = 2.56°$$

for a spectrometer resolution of $(\Delta E / E) = 1 \cdot 10^{-4}$ with $E_0 = 100$ MeV and $E_{acc} = 5$ MeV/m.

Cavity steering effects are significant and require correction of the beam optics especially if cavities at the beginning of the linac are phased. Manual phasing with the spectrometer has been proven to be very time consuming but is required only once for initial phasing of the accelerator. Periodic phase corrections are performed using automated algorithms. It is expected that the resolution will increase significantly when a Beam Position Monitor (BPM) in the arc at a location with a higher dispersion of 10 m is used.

Automated Phasing

The above described method has been automated. The view screen for the beam position measurement is replaced by reading from a beam position monitor with a position resolution of 0.2 mm. It is also possible to use a harp reading. The BPM is located in the spreader section at a location with a dispersion of 1.1 m resulting in an energy resolution of $1 \cdot 10^{-4}$. The algorithm changes the phase in an individual cavity by $\Delta\phi = \pm 30°$, measures the initial beam position and the beam positions following the changes in phase, and calculates the crest phase from the three measured positions according to

$$\phi_{crest} = \tan^{-1}\left[\frac{x_1 - x_2}{x_1 + x_2 - 2x_3} \cdot \sin\left(\frac{\Delta\phi}{2}\right)\right] + \phi_0$$

ϕ_0 : initial phase setting

x_3 : beam position for $\phi = \phi_0$

x_2 : beam position for $\phi = \phi_0 - \Delta\phi$

x_3 : beam position for $\phi = \phi_0 + \Delta\phi$

$\Delta\phi$: change in phase setting

For a final energy of 100 MeV and a cavity gradient of 5 MV/m, a phase change of 30° results in a position change of 7.4 mm assuming a dispersion of 1.1 m.

The accuracy of this method is $\approx \pm 2.5°$ and takes 20 seconds per cavity. Most of the time is required for the averaging of the BPM signal to achieve a resolution of 0.1 mm. This takes about 4 seconds. The automated phasing is only successful if the phase is set within ± 90°. Therefore initial manual phasing is required. The experimental verification of this algorithm showed that the linac energy was increased by 1.8 MeV at an initial energy of 119.6 MeV. Reproducibility has been verified by changing the initial phase by 5° and 10°, and the automated algorithm determined the same crest phase within ±2.5°.

IV. PHASING WITH BEAM–INDUCED TRANSIENTS

This method requires pulsed beam. Typical beam conditions are I_o=200 µA, τ_b=20 µs (pulse length), and f_r=60 Hz. The average beam current is less than 1 µA and therefore does not require machine protection by the beam loss system. The expected transients for the gradient signal have been discussed in [2]. Unity gain of the control loop is typically ≈10 kHz and therefore the effect of the gradient control loop is small during such a short pulse. The control system regulates the average of the gradient.

The observed transient amplitudes for the above described beam conditions are 170 mV for = 0° (on crest) and ±1.5 mV for phase settings ±5° from the zero crossing at ±90°. The result of a measurement is shown in Figure 1. The observed amplitudes are consistent with the calculations except close to zero crossing. The transients at zero crossing are a result of the beam loading in the buncher, which causes the phase of the electron beam to change by ≈ 2° during the macropulse of 20 µs. This is due to the fact that the buncher cavity is not operated at zero crossing and that the RF control system is not designed to correct for fast transients. The signals in Figure 1 are averaged over 64 samples to improve the signal-to-noise ratio. This method allows cavity phasing better than ±2° if only the first 2 µs of the transients are observed to determine a change in sign for the transients.

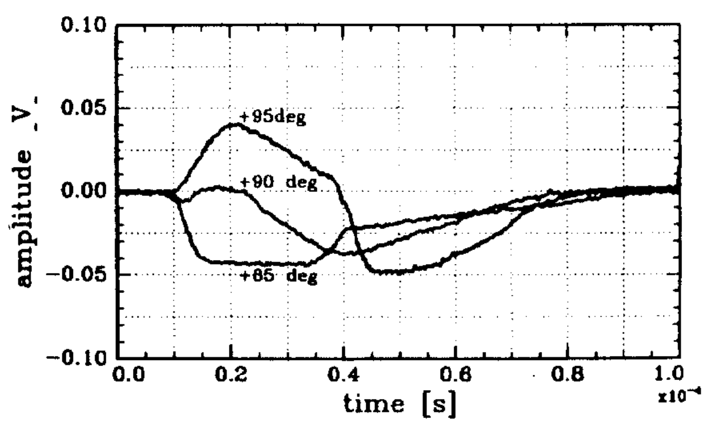

Figure 1. Measured beam-induced transients. Phase at zero crossing and ±5°. I_O = 250 µA, τ_b = 20 s, f_r = 60 Hz. Signal amplified by 30 dB.

It is possible to implement the transient phasing method in the embedded microprocessor code for the RF control module using the module internal digitizer. The gradient error signal is amplified by 50 dB and will be sufficiently large compared to 2.5 mV ADC resolution to determine the phase better than ±5°.

V. PHASING WITH BEAM MODULATION

This method is similar to the phasing with transients since it uses beam-induced gradient fluctuations to determine the phase at zero crossing. The beam current is modulated as

$$I = I_0 + \Delta I \cdot \sin(\omega_m t)$$

ΔI : amplitude of current modulation (typ. 1 μA)

ω_m : frequency of current modulation (typ. 100 Hz)

The beam-induced gradient will be 6.4 kV/m resulting in a detector error of 6.4 mV (5 V≡5 MV/m) if the gradient loop is open. This translates into ≈ 6 mV gradient modulator drive (at 100 Hz) if the gradient loop is closed. The spectrum of the gradient modulator drive is shown in Figure 2. The dominant microphonic noise component at 56 Hz has twice the amplitude, and the broadband noise within a bandwidth of 50 kHz as acquired by RF control module internal ADC is 20 mV_p. The signal is too small to be analyzed within the RF control module, but if processed in the machine control room using the analog monitor system [3], it is possible to phase cavities better than ±5°.

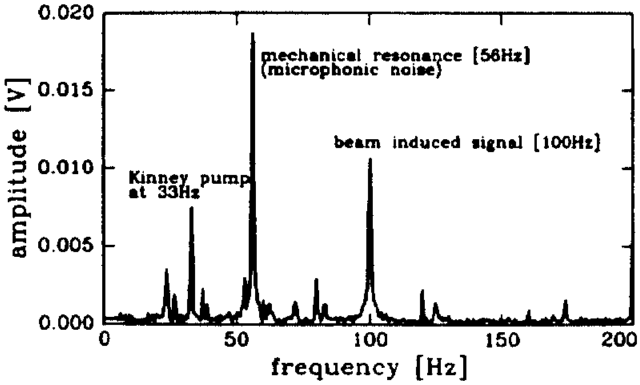

Figure 2. Spectrum of gradient modulator drive with modulated beam. $\Delta I = 1$ μA and $f_m = 100$ Hz.

VI. PHASING WITH BEAM-INDUCED GRADIENT

This method requires CW beam. At least 10 μA of beam current is required to excite a sufficiently large field gradient to measure a phase error relative to the phase reference derived from the master oscillator. The cavity is not powered by the klystron. The phase setpoint is adjusted to null the phase error signal. Typical sensitivity is 100 mV/degree at 5 MV/m or 1.27 mV/degree for 10 μA of beam current which excites a field of 63 kV/m. The slope of the zero crossing must be negative to guarantee that the phase of the beam is 0° and not 180° out of phase. The phase setpoint determined by this method is then used with gradient and phase loop closed to accelerate beam on crest.

The phase of the beam-induced voltage is offset by the detuning angle which is measured with an accuracy of ±5°. The precision of the detuning angle measurement limits therefore the accuracy of this otherwise very precise measurement.

VII. CALCULATED PHASE SETTINGS

The phase of the accelerating field relative to the beam can be calculated from known electrical length of cables, other control module components such as the down converter, and the time of flight of the electron beam converted to phase. All signals are referenced to a common master oscillator. Cable length of more than a kilometer over the whole accelerator site and effects from temperature changes do not allow for high accuracy. Nevertheless it is possible to calculate the phase difference between the cavities in one cryomodule within ±5°. The probe cable length and phase offsets in the control module can be measured better than ±2° as achieved in recent tests. Also errors in time of flight due to mechanical position of the cavity, which can change by up to ±0.5 cm as function of tuner position, contribute to the overall error.

VIII. CONCLUSION

Several methods for the adjustment of the phase of the accelerating field have been tested in the CEBAF accelerator during the commissioning phase of the north linac. Phasing with the spectrometer is time consuming especially for the initial phasing for the accelerator. Once the cavity phase is adjusted within ±40° an automated algorithm will correct for drifts. Only one cavity can be done at a time. Other methods allow for simultaneous phasing of several cavities and are therefore, since faster, more desirable during accelerator operation. The cavity phasing using beam modulation can possibly be used while beam is delivered to the experiments. A comparison of the different methods is given in Table 3. The most sensitive method is the phasing using beam-induced gradient in CW mode, but it relies on precise knowledge of the detuning angle.

Table 3: Comparison of the Phasing Methods

Method	Accuracy aver. (best)	Dedicated beam time	Multiple cavities simultaneously
Spectrometer	±3° (±2°)	No	No
Beam ind. trans.	±2° (±1°)	Yes	Yes
Beam modulation	±5° (±2°)	No	Yes
Beam ind. grad.	±5° (±3°)	Yes	Yes
Calculation	±5° (±2°)	No	Yes

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IX. REFERENCES

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