BEAM-BASED PHASE MONITORING AND GRADIENT CALIBRATION OF JEFFERSON LABORATORY RF SYSTEMS

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Abstract

Beam-based monitoring was instituted at Jefferson Lab in December of 1994 to correct the RF system phase setpoints against drifts of the master oscillator system, while running transparently to normal beam setup and delivery operations. As then implemented, the master oscillator distribution was subject to large thermal drifts, but no means existed of tracking the distribution of drifts, nor of identifying phase errors for individual cavities following maintenance activities. The background process implemented is capable of cresting each of the 312 cavities in the linacs to within approximately ± 2 degrees. In addition, during dedicated system measurement operations, the RF cavity gradients have been calibrated with beam to within a tolerance of approximately $\pm 5\%$. These beam-based results are in many cases more than 20% different from commissioning results using RF measurement techniques.

1 INTRODUCTION

The Continuous Electron Beam Accelerator Facility (CEBAF) consists of two recirculating electron linacs and the associated beam transport lines. Each linac provides a nominal energy gain of 400 MeV, up to five passes, for a final energy of 4 GeV. The injector provides three interleaved 499 MHz electron pulse trains with independent current control, one for each of the three experimental halls.

2 CRESTING THE LINAC PHASES

During accelerator commissioning, phase drifts in the master oscillator distribution hampered multipass operations, requiring re-adjustment of linac phase setpoints as often as several times per hour. Residual dispersion in the machine rendered detailed setup or measurement operations very difficult. As a result, correction processes called “energy locks,” supported by analogous “orbit locks,” were instituted [1, 2], providing 0.1 Hz bandwidth feedback stabilization of the beam position and energy at selected points within the system.

The energy locks stabilized the energy gain for the first pass beam, but not the accelerating phase (or the energy spread) of the beam. In November of 1994, we measured the resolution and stability of the energy lock process as a beam energy monitor and found that the scatter of measurements of the relative beam energy was approximately 5×10^{-5}. This performance was adequate to support an automatic cresting process for the phase setpoints of the RF system. The algorithm is described below. All individual cavity, cryomodule global, and linac global setpoints (available as single parameters in the control system) are available to the process. The resulting “AutoKrest” program [3] became the “phase lock” for CEBAF operations, and has been of great use in documenting residual phase drifts and faulty hardware in the system. The process has been stable for use while delivering CW beam to experiments, but as target requirements for energy stability become more stringent, we are less able to run the process during regular beam delivery.

2.1 Measurement Algorithm

The time scale of changes in the RF system (tens of minutes) and response time of the energy locks (5 seconds for each of the several updates required for convergence after an energy shift) implied that data for the cresting process would be very sparse. Accordingly, we chose an algorithm requiring the practical minimum (two) of data points. This provided the ability to crest a single RF phase in approximately one minute with the algorithm given below.

The RF system of a linac is divided into the energy lock cavities, the cavity or multiple cavities under test (which might include the energy lock cavities), and the rest of the linac (if any). For the first-order determinations required, the cavities of the energy lock process were presumed on-crest. The phase of an individual RF system is given relative to zero as the on-crest value, with ψ as the (slowly varying) error of the setpoint from that zero point. The total linac energy E, fixed by the energy lock process to within approximately 5×10^{-5}, is

$$E = E_{\mathrm{other}} + E_{\mathrm{lock}} + E_{\mathrm{test}} \cdot \cos(\psi) + \mathrm{error}.$$

If one adjusts the phase setpoint of the test system by $\pm\Psi$, successively, after some simplification one obtains

$$\frac{E_{\mathrm{lock}}(+) - E_{\mathrm{lock}}(-) + \mathrm{error}}{2E_{\mathrm{test}}} = \sin\psi \cdot \sin\Psi.$$

2.2 Precision

The differential resolution of beam energy is better than 10^{-4} of the total linac energy gain. With 160 cavities in each linac, the precision with which the relative energy gain of any cavity can be measured is better than 1%. For the case of a single RF cavity, using degree rather than radian measure for the phases and the small-angle expansion for the sine function, and including the overall error in energy

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determinations, we may write the relation above as:

$$\psi \cdot \Psi = \left(\frac{180}{\pi}\right)^2 \cdot \frac{E_{\mathrm{lock}}(+) - E_{\mathrm{lock}}(-)}{2E_{\mathrm{test}}} \pm \sim 20$$

The uncertainty for a single cavity cresting measurement is equivalent to approximately 20 square degrees. Using a 10 degree shift in the cavity phase results in an overall energy shift (presuming a starting value near crest) of only 10^{-4}, and an anticipated error in determination of the crested phase setpoint of approximately 2 degrees. These estimates are confirmed by monitoring of successive determinations of the crest phase of given RF systems and by monitoring of the total system energy.

The most frequent problem with this algorithm is the influence of other components in the RF system, which also affect the energy lock gradient setpoints (other cavities going out of gradient lock, manipulation by operators, etc.).

2.3 AutoKrest Implementation

Implementing AutoKrest as a Unix process accomodated the need for for frequent modification during development. However, the other Unix control processes (energy and orbit locks) had user interfaces limited to the single screen from which they were invoked. To allow multiple users to control or monitor the progress of AutoKrest without spawning interfering processes, multiple instances of AutoKrest were prevented by using lock files as flags in the file system. The lock file contents provide CPU, process ID, and certain other useful information for later queries of the system to verify the status of the process. This has proven to be very useful and robust. A control interface usable from multiple operator screens was implemented using the Tcl/Tk language as extended to communicate with the EPICS database fields of the control system. To speed implementation, we began writing a Unix-based data acquisition, sequencing, and analysis task and an operator interface to connect the Unix program through a set of EPICS records accessible to a computer interface screen.

Because there was no other easily monitorable parameter to determine the status of the energy lock, we chose to monitor the gradient setpoints used by the lock to stabilize the overall system energy. These were updated at a nominal 0.2 Hz rate. We determined that it would be sufficient for AutoKrest to acquire data until the standard deviation of the last three data points was less than a threshold value. If a cavity or the rest of the RF system were particularly noisy, or if some other stimulus were being applied to the beam energy, the series of energy lock setpoints would not stabilize. This was the primary protection against AutoKrest introducing phase setpoint errors into the RF system.

The master oscillator system has been stabilized since AutoKrest was introduced, and this protection is marginal, as we have found examples of RF system behavior which can mislead AutoKrest. Several enhancements are planned to improve the performance of AutoKrest, notably the incorporation of an AC coupled operation mode (as used in [4]) and algorithmic improvements to allow use of all available data for consistency checks.

3 RF GRADIENT CALIBRATIONS

The fine energy resolution in the arcs has also been used to check the gradient calibration of the RF systems in both linacs last summer and again this spring. The gradient calibration for each RF system was obtained from the careful measurement of many independent pieces of hardware during cavity and RF commissioning, and was subject to many different sources of error. Calibration with beam yields an overall system response which is not subject to cumulative error buildup. In the first calibration of the linacs, one entire 8-cavity cryomodule was found in which the gradients had been overestimated by from 25% to 30%. Errors of this magnitude were few, and some have been found to be due to aging of RF modules left in service for two years before recalibration.

3.1 Protocol and Errors

The path we have taken to date is based on a null technique: with a reference cavity turned off, adjust the linac energy to the desired value; then successively turn each cavity in the linac off while supplementing its energy gain using the reference cavity. After a relative calibration of each cavity against the reference cavity, the absolute calibration is obtained from the known total beam energy.

The dominant error source is the variability of the total beam energy from random variations within the linacs. With the energy lock off, the energy is sometimes stable at the 5×10^{-5} level, but at other times may oscillate at a level as high as 10^{-3} with a period of a few minutes. We have not yet traced the source of this behavior. Comparison of each cavity against the reference takes approximately 20 seconds, and we periodically monitor the total linac energy to allow correction for drifts. We now track the background beam energy to about the 1–$2 \cdot 10^{-4}$ level, so this source introduces errors of about 2% of a typical gradient for the first linac and 3% for a typical cavity in the other linac.

Each cavity in the 400 MeV linacs gives 2 to 4 MeV to the beam. The 2.5 MeV average is roughly 0.6% of the total energy of the beam in arc 1 and 0.3% of the total energy in arc 2. Turning each cavity off to make a differential energy measurement is possible, but can introduce errors from exceeding the linear field region of the bpms and of the quadrupoles. The errors from this type of measurement appear to be greater than those involved in the null measurement described above. Adjusting the arc dipole current to maintain the beam position would be reasonable but for the need to check for drifts in the total energy from the rest of the linac and because the solid iron dipoles need excessive (on the time scale of these measurements) amounts of time to settle in field after changes in current.

One weakness of the technique used is that it relies upon linearity between the gradient setpoint and the actual cavity gradient. As this is one of the primary bench tests for the

RF module calibration, we have considerable confidence in it. We have not yet made specific online linearity tests, although we plan to do so.

3.2 Stability of Results

The first attempts at this gradient calibration were in April, 1996, with both linac calibrations being completed in May, 1996. The measurements were useful in identifying some spurious gradient calibrations. After downloading corrections to the RF modules, we repeated the measurements in mid-summer. The correction factors found in the May 1996 calibration run are shown in Fig. 1. In addition to apparent errors from some of the commissioning analysis, we found some isolated cases of hardware which had drifted significantly in calibration. One set of 8 RF modules which had been in service for the two years since the earliest commissioning of hardware was replaced with freshly calibrated modules and recalibrated as a test. One slot had a gradient change of 15%. This shift was due to drift of the response of the gradient measurement diode. Verification of calibration for new modules is desirable to avoid such a reintroduction of errors. In the results shown below, some corrections made after the May measurements showed up inversely in the 1997 measurements, after routine replacement of the RF modules.

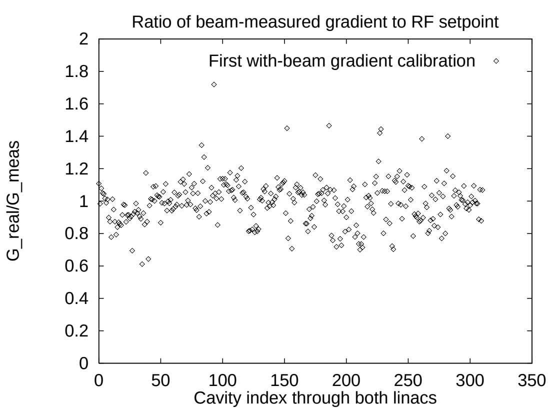

Figure 1: First measurement of linac gradient errors

The 1996 and 1997 gradient data are in good agreement for most of the linac cavities (Fig. 2). We had not recognized the necessity of tracking drifts in the two linacs as of the May, 1996, calibrations, and some of the fine structure visible in the later data may be an artifact of these drifts. Many large outliers are in slots in which RF modules were changed between the calibration runs. Systematic module installation records were not kept until recently, so we cannot determine whether all of the discrepancies occurred at module changes.

4 OUTLOOK

AutoKrest remains an essential tool for identifying and compensating for phase drifts, which also aids in targeting corrective actions. Improvements in the algorithm and

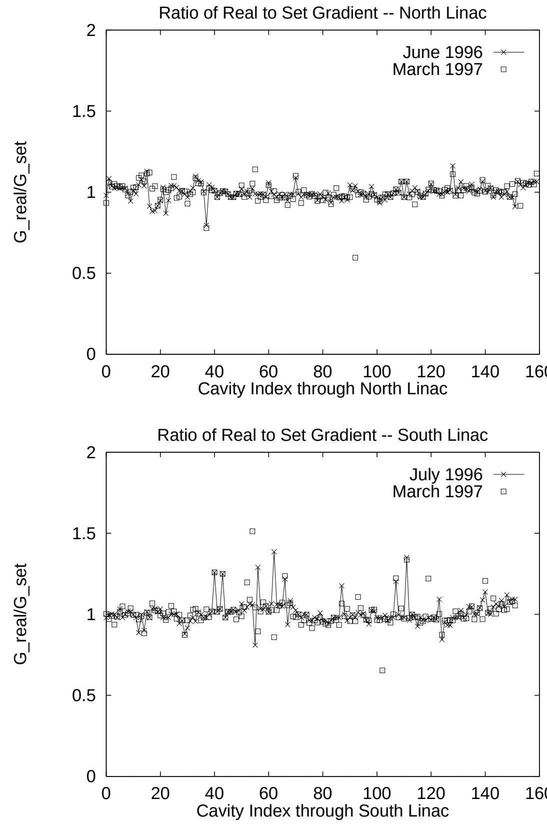

Figure 2: Measured Gradient ratio comparison from June/July, 1996, to March, 1997, for the North and South Linacs at CEBAF. Note the persistence of fine structure over the nine month interval between measurements.

sensing techniques will enable the necessary monitoring to be completed during periodic experimental hall accesses.

The crest phase setpoint and detuning angle mixer offset (part of the tuner tracking process) are routinely measured when RF modules are replaced. The crest measurement already requires beam and it is desirable to check the gradient calibration against a few reference cavities at the same time to prevent the “inverse error” problem noted above. It is also desirable to dedicate the few hours required for a gradient calibration check at the start of each run period, as many RF modules will have been replaced with freshly calibrated ones. This provides an opportunity for a final validation before they are qualified for service.

5 REFERENCES

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