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AUTOMATION OF THE ReAccelerator LINAC PHASING*

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Abstract

At the MSU-NSCL ReAccelerator (ReA) facility [1, 2] one of the major time-consuming tasks during beam preparation is the linac phasing. This procedure has been improved and automated using a combination of routines based in EPICS, CS-Studio and python. These routines scan the cavity phase delay and use the change in beam energy to determine the accelerating phase of a cavity. Simulations were carried out to determine the constraints that the application would face with beam before the application was tested on the ReA linac. The automated procedure provides identical results to the previous, but with reducing the time required to phase a single RF cavity to as low as 146 seconds.

INTRODUCTION

At ReA, a stable 1+ beam from local sources or a rare isotope beam stopped in a gas cell, is injected into a Beam Cooler-Buncher (BCB) where it is bunched and cooled. Afterwards, the beam is charge bred in an Electron Beam Ion Trap (EBIT) to higher charge states, and the desired beam component is selected using a charge over mass (Q/A) separator. The selected beam is then initially accelerated using a Radio-Frequency-Quadrupole (RFQ) up to 530 keV/u. The beam is after accelerated by a linear accelerator (linac) composed by four superconducting cryomodules with 23 quarter-wave resonating cavities, and delivered to different experimental setups.

Linac Phasing

Phasing the ReA linac is required in order to accelerate the beam beyond the energy of the RFQ. In the case of beam energy much higher than the energy gain in a cavity, the relationship between the beam energy and RF cavity phase is well known to be [3]:

$$E_{Final}(\phi) = E_0 + qV\cos(\phi - \phi_{offset})$$

where E_0 is the beam energy of the particles entering the cavity, ϕ is the cavity phase set point, ϕ_{offset} is the phase offset of the cavity relative to the RF reference line, q is the electric charge of the beam ions, and V is the RF cavity effective voltage. The phasing process consists of setting the correct accelerating phase of an RF cavity ($\phi - \phi_{offset}$). This is done by changing the phase set point of the RF cavities and measuring the corresponding energy. The phase is changed until the value where no acceleration occurs is found. From this value one can determine the desired acceleration phase for that particular cavity.

Beam preparation time contains several important tasks to ensure that the delivered beam has the characteristics required for each experiment. The linac phasing is one of the most time-consuming steps in beam preparation, since presently there are up to 23 RF cavities to phase, usually with a very low beam intensity. In addition, operators will often need to re-steer the beam during and after phasing a cavity, especially at low beam energies. Speeding up this process allows more time to be spent on other beam preparation tasks and essentially having a higher beam availability to experiments.

METHOD

The new phasing procedure performs an automated scan of the RF cavity phase against the relative beam energy in order to find the zero-crossing (no acceleration) phase. In more detail, the phase scan goes through the full range of the RF cavity, from -179° to 179° in steps of at least 60°, and at each phase it collects a spectrum from a silicon detector located in the straight section after the cryomodules. The spectrum is automatically fitted with a Gaussian function and the centroid value is stored. The correlation plot of the centroid value and the phase is finally fitted by a cosine function whose fit values determines the accelerating phase. Figure 1 presents the schematic view of the phasing method.

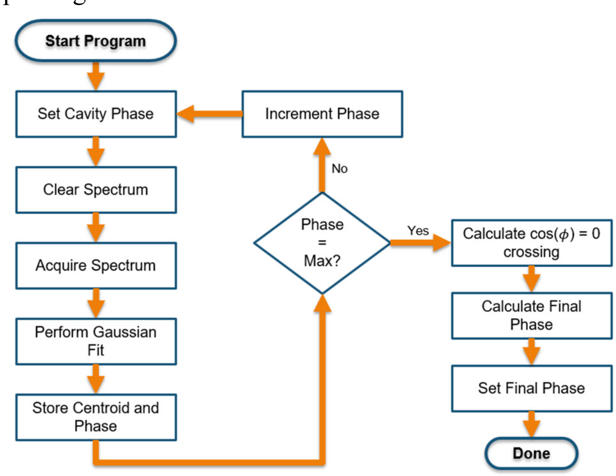

Figure 1: Diagram of phasing application main loop. This loop is done for one cavity. For certain phases, the beam energy gain is measured with a silicon detector. After scanning the phases, a cosine function is used to determine the phase where there is no energy gain (cos(φ)=0) and the final/accelerating phase to apply to the cavity.

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Phasing Application Development

The automated phasing application was developed using a combination of Experimental Physics and Industrial Controls System (EPICS) Input/Output Controllers (IOCs) and Python scripting. EPICS IOCs contain process variables (PVs) that are broadcast throughout the laboratory's controls network, which allows operators to control devices and monitor data using Control System Studio (CS-S) interfaces. The Python scripts are controlled via these IOCs, which allow them to be started and stopped through the CS-Studio interfaces at any time.

There are two main IOCs used for phasing automation: the first to receive and analyse data from a silicon detector, and the second to run the main phasing program. The first communicates and retrieves data from a silicon detector, and allows the data to be stored in PVs that can be displayed and controlled through a CS-Studio interface. The CS-Studio interface shows the full silicon detector spectrum, a region of interest, device and IOC controls, and analysis tools such as a Gaussian fitting function.

Safety Precautions

Machine safety was a priority when designing the phasing program, and several considerations were taken into account when deciding what PVs were accessed and how. The main safety feature is the omission of any voltage control PVs for the RF cavities, which would prevent the cavities from continuously ramping if any problems with the program were to occur. Additionally, the program continuously looks at the beam count rate on the detector and will insert a Faraday Cup to block the beam if the count rate exceeds a threshold set by system experts in order to prevent any damage to the silicon detector. This was meant to assure that only consequence of the program malfunctioning would be changing the RF cavity phase, which wouldn't have any potential for damaging equipment.

The phasing program checks for several conditions before taking each action in order to ensure that the scan will complete successfully. There are three conditions that will abort the program, including an RF cavity interlock, a user stop command, and a data acquisition (DAQ) timeout counter. All of the RF cavity interlocks are summed up in a separate summary PV that, when active, will either stop the phasing program or prevent it from starting. The data acquisition timeout counter is a PV that increments every second that the program is collecting data from the silicon detector and resets itself when the minimum counts threshold has been met. If the DAQ timeout counter passes a preset threshold then the program will stop, which was designed to prevent the program from running continuously. There are three additional checks that will pause the program, two for the count rate on the silicon detector being too high or low, and one for a manual pause command. The program checks for whether or not the count rate is above or below a predefined threshold, and will pause and prompt operators to adjust the count rate before resuming.

Initial Testing and Simulation

To initially test the phasing program, we developed a simulated IOC, which provided data from an event generator that mimicked the spectrum from the silicon detector. This data was then used to phase a simulated version of the ReA linac. The simulated IOCs contained the same type of PVs that the final IOCs have, such as RF cavity phase and amplitude, interlocks, on/off status, phasing parameters, and detector spectra and controls. The simulated data was then displayed using CS-Studio, where we were able to develop and refine the design of the interface simultaneously during testing. The simulated phasing program was used to test, debug the automation process, and also define standard parameters such as the minimum number of spectra necessary to acquire to determine the accelerating phase accurately.

RESULTS

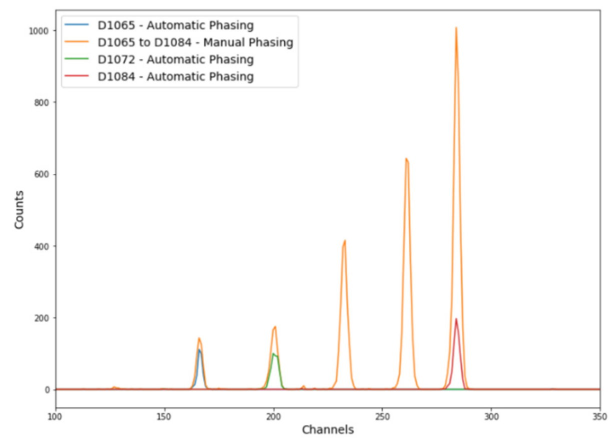

Figure 2: Silicon detector spectra of manually phased and automatically phased RF cavities taken during initial testing. The spectrum of the manually phased cavities were taken by turning off five sequential RF cavities before beginning the automatic phasing test.

The program was successfully tested with beam during beam preparation for an experiment in February of 2021. The test consisted of phasing 15 RF cavities and comparing the results with previous manual phasing results. The automatic program achieved the same results as those done using a careful manual phasing procedure, with the difference in phase being on the order of 0.1° for any given cavity. The silicon detector spectra taken during this test were recorded and compared to verify the energy gain of the beam was consistent between automatic and manual phasing as shown in Fig. 2. Regarding the time required to phase, automatic phasing was completed significantly faster than manual phasing on average. The speed of phasing each cavity varied from 146 to 600 seconds, but a majority yielded times closer to the fastest time.

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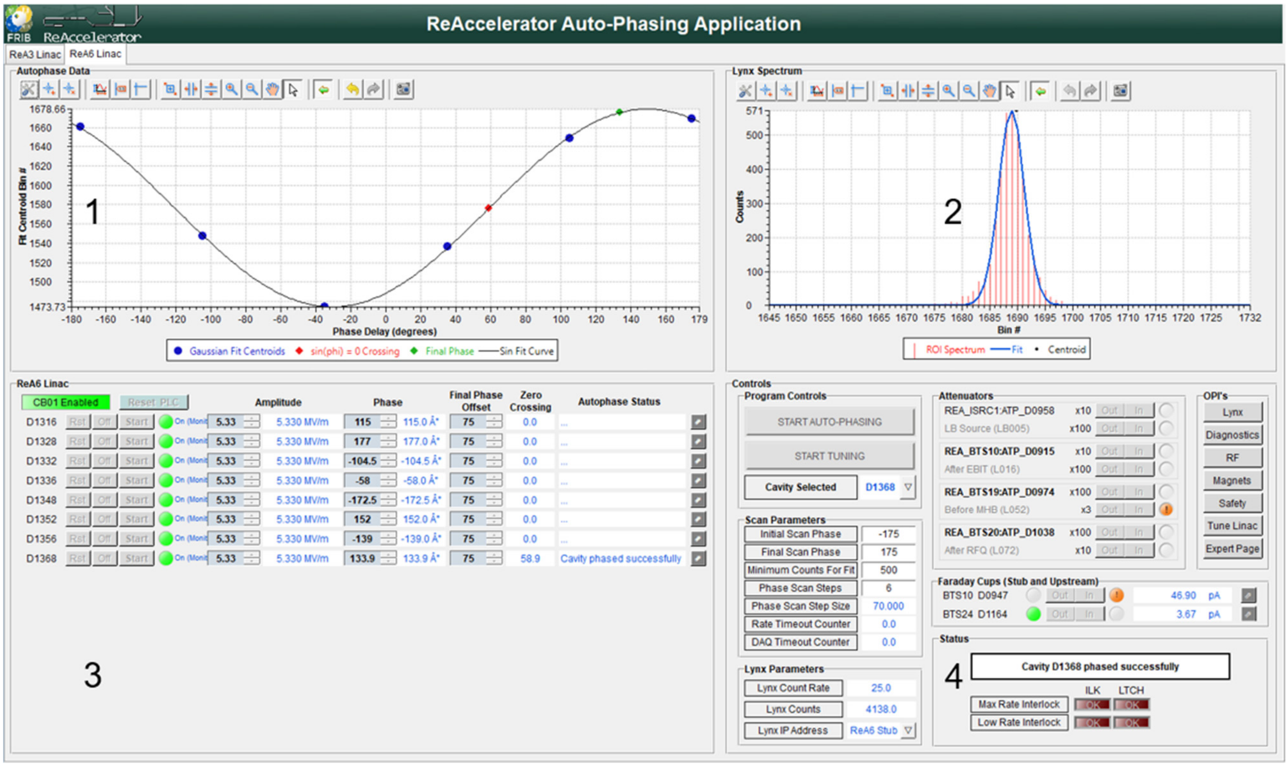

Figure 3: The ReAccelerator Auto-Phasing Application CS-Studio interface, which is used by operations to monitor and control the phasing program. Key areas of the interface include the phase scan results that contains the energy vs phase plot and the calculated zero crossing phase (1), silicon detector spectrum (2), RF controls and cavity phasing statuses (3), and operator controls containing the program controls, scan parameters, diagnostics, silicon detector count rate interlock displays, and program status (4).

Interlock Testing

Specifically engineered interlocks of the application were also tested during the initial phasing test. In particular, the interlocks where the operator must take action were tested and successfully paused the phasing program as designed. These were initially done by changing the interlock thresholds to well below normal values in order to force normal beam count rates to trigger the interlocks. Once this was done successfully the interlock thresholds were changed back to the values assigned by system experts, and have properly triggered the interlocks during abnormal events while phasing.

Phasing Application Interface

The phasing application interface was designed to contain all of the information that operators need for phasing using the automated phasing program as well as phasing manually, as presented in Fig. 3. It contains all of the controls and diagnostics required to complete all of the phasing tasks, and reduces the amount of CS-Studio screens required for phasing. Additionally, while the program is running status messages displayed for both the individual cavities and the overall status of the program are updated and displayed. The interface also includes displays of the ROI selection of the silicon detector spectrum as well the data from the phase scan, both of which update automatically as the program progresses through the scan.

CONCLUSION

The phasing automation program has been a success in speeding up and simplifying the process of phasing, and is currently part of the standard beam preparation procedure for phasing the ReA linac.

Future goals for this project include refining and adding features to the program and OPI, updating the program for use in future ReA linac additions, and updating the program to phase all cavities sequentially.

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