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# PHASING OF SUPERCONDUCTIVE CAVITIES OF THE REX/HIE-ISOLDE LINAC

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*Abstract*

ISOLDE is a facility dedicated to the production of a large variety of Radioactive Ion Beams. The facility is located at the European Organization for Nuclear Research (CERN). In addition to two target stations followed by low energy separators, the facility includes a post-accelerating linac with both normal conducting (REX) and superconducting (HIE-ISOLDE) sections. The HIE-ISOLDE section consists of four cryomodules with five SRF cavities each that need to be phased individually. In this paper, we will describe the procedure and the software applications developed to phase each of the cavities as well as improvements that will be introduced in the near future to reduce the time it takes to complete the process.

## INTRODUCTION

ISOLDE is a research facility dedicated to the production of radioactive isotopes located at CERN in Geneva, Switzerland. Isotopes are produced by bombarding a thick and heavy target with a 1.4 GeV proton beam from the Proton Synchrotron Booster (PSB). After diffusion out of the target, the isotopes are ionized, electrostatically accelerated up to 60 keV and mass separated in a dipole magnet. The resulting Radioactive Ion Beam (RIB) is then delivered to one of the experimental stations located in the experimental hall directly at low energy or after being accelerated using the REX/HIE-ISOLDE post-accelerator [1]. Before injection into the linac, the RIB is bunched and transversely cooled in a Penning trap (REX-TRAP) and is charge bred to decrease its mass-over-charge ratio (A/q) by stripping of electrons in the REX-EBIS [2] where the trapped ions are bombarded with an electron beam. Extracted ions with an A/q between 2.5 and 4.5 can be accelerated in the linac and transported to an experimental station through one of the three High Energy Beam Transfer lines (HEBT). With the completion of HIE-ISOLDE [3], the normal conducting part of the linac was extended with four cryomodules (CM1-CM4) each equipped with five superconducting Quarter Wave Resonator (QWRs) and a superconducting solenoid for transverse focusing. This upgrade has increased the maximum available energy significantly and it is currently able to reach 10 MeV/u for light beams. The HIE-ISOLDE linac was designed with a -20 degrees synchronous phase (i.e. +70 degrees from the bunching zero-crossing). Each cavity is powered by its own RF amplifier and they can be phased separately. For the linac to be correctly set-up and to reach the desired beam energy, the cavities need to be correctly phased with respect to the time of flight of the ions.

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## PHASING USING A SILICON DETECTOR

The silicon detector is a very sensitive device, capable of resolving single particle events and can therefore be used to directly measure the energy of very low intensity beams like the ones typically available at RIB-production facilities. A Silicon detector located in the Diagnostic Box 1 (DB1) has been regularly used during the last few years to phase the normal conducting cavities of the REX linac. In a similar way, a second detector located in DB2 was used to phase the superconducting cavities. The energy of the beam was measured (top of Fig. 1) as the phase of the SRF cavity was changed. Once enough measurements were completed, the sinusoidal fit of the data (bottom of Fig. 1) could be used to determine the zero-crossings and the synchronous phase of the cavity.

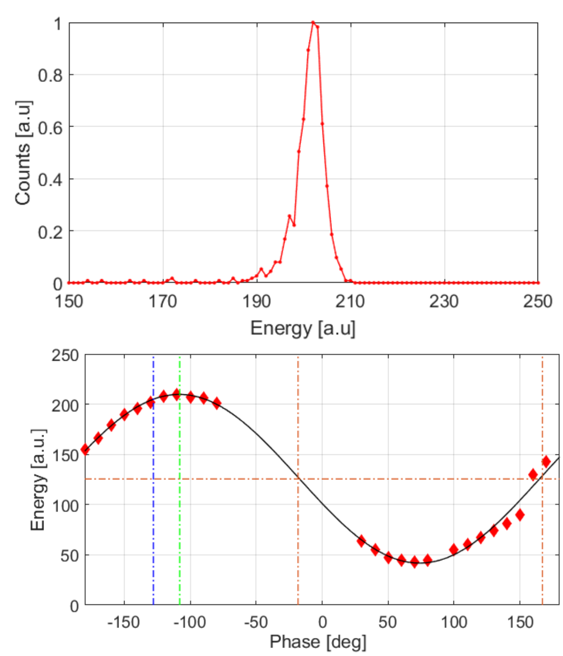


Figure 1: On top, energy spectrum measured by the Silicon detector in DB2 during the phasing process of the first superconducting cavity in the linac (SRF01). At the bottom, beam energy measured by the Silicon detector as a function of the RF phase in SRF01 in red, sinusoidal fit in black, cavity zero-crossings in brown, peak acceleration in green and synchronous phase in blue.

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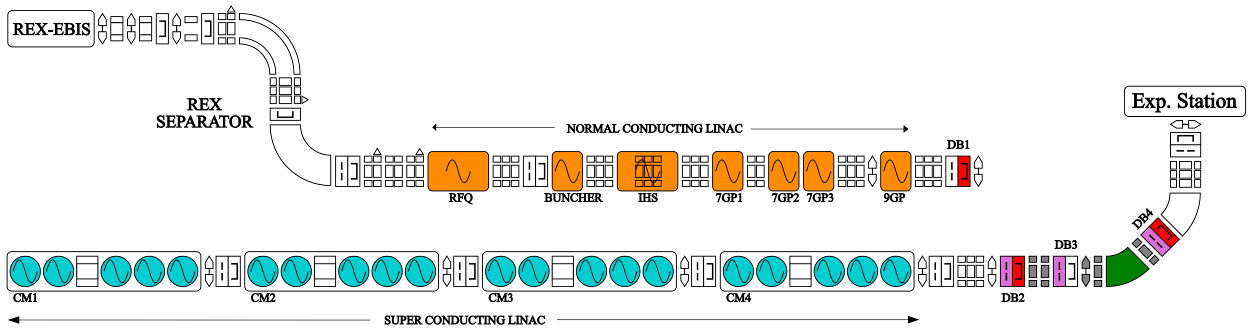


Figure 2: Simplified layout of the REX/HIE-ISOLDE linac. Normal conducting RF cavities in orange, superconducting cavities in blue, collimating slits in purple, Faraday cups and Silicon detectors in red, 45 degree dipole magnet in green, cryomodules labelled CM1 to CM4 and relevant diagnostic boxes labelled DB1 to DB4.

Even though phasing the cavities using the Silicon detectors is feasible and it was particularly useful to complete the beam commissioning of the REX linac before the HEBT lines were ready for beam, there are several issues that limit their usability in an operational environment. For example, special care must be taken to adjust the beam intensity to avoid pile-up effects (impossibility to discern two events too close in time) and saturation. Furthermore, the detectors deteriorate with time due to radiation damage negatively affecting the precision of their measurements.

## PHASING USING A DIPOLE AND A SILICON DETECTOR

In a next step, instead of measuring the energy directly on the Silicon detector, we decided to use the first dipole of the HEBT line (in green in Fig. 2) as a spectrometer. This time the Silicon detector in DB4 was used as a very low beam intensity monitor (particle counter). Three 1 mm vertical slits (in purple in Fig. 2) are inserted in the beam line and all focusing and steering elements (in grey in Fig. 2) are turned off to select only the particles travelling along the beam axis and increase the precision of the measurement. When needed, the beam intensity is further lowered by inserting beam attenuators with different transparency ratings after the REX separator. The magnetic field of the dipole is fixed at a value corresponding to the initial beam energy and by scanning the phase of the cavity across the 360 degrees we are able to identify the two zero-crossing phases. After setting the phase at + 70 degrees respect to the bunching zero-crossing, the magnetic elements are scaled to the new energy and the overall beam transmission is verified.

## PHASING USING A DIPOLE AND A FARADAY CUP

Using the Silicon detector as a particle counter reduces the impact of the problems generated by the radiation damage but doesn't solve the pile-up and saturation effects and it doesn't eliminate the need to continuously adjust the beam intensity.

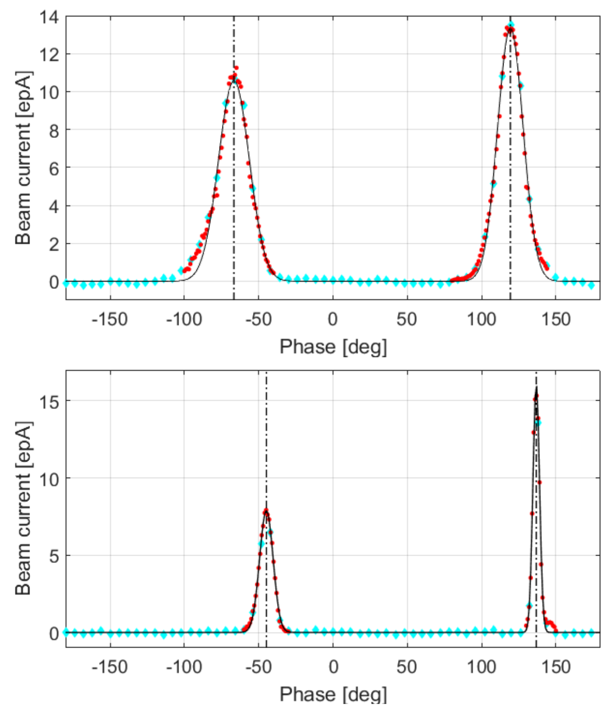


Figure 3: Typical phase scans measured during the phasing process of the different SRF cavities of the linac (high relative energy gain on top, low relative energy gain at the bottom). Results of the rough scan in light blue, fine scans in red, Gaussian fit around zero-crossings in black.

In addition to a Silicon detector, DB4 is also equipped with a Faraday cup (FC) that can also be used to measure the beam intensity, but the sensitivity of such device is limited to a minimum of 100 efA. In order to be able to use the method described in the previous section but replacing the Silicon detector with the Faraday cup, focusing elements in the line are not turned off and a single 5 mm slit after the dipole magnet is used. Two examples of these measurements are shown in Fig. 3. Typically, an initial phase scan is performed at steps of 5-10 degrees to identify the regions of interest (in blue), followed by a high resolution scan (in red) to de-

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termine the zero-crossing phases. The uncertainty of this method ranges between 1-2 degrees when the relative energy gain is high (i.e. cavities in the first cryomodule operated at high gradients) and 5 degrees when the relative energy gain is low (i.e. cavities in the last cryomodule operated at low gradients).

## ENERGY MEASUREMENT

The beam energy and energy spread are usually measured every time the phasing procedure is completed. Three 1 mm vertical slits are inserted in the diagnostic boxes and the focusing and correcting elements after the first slit are turned off (see Fig. 2 in purple and grey). The beam intensity is measured as a function of the magnetic field of the dipole using the Silicon detector in DB4 as a very low intensity particle counter. The magnetic field in the dipole is measured precisely using a Hall probe. An example of such measurement is shown in Fig. 4.

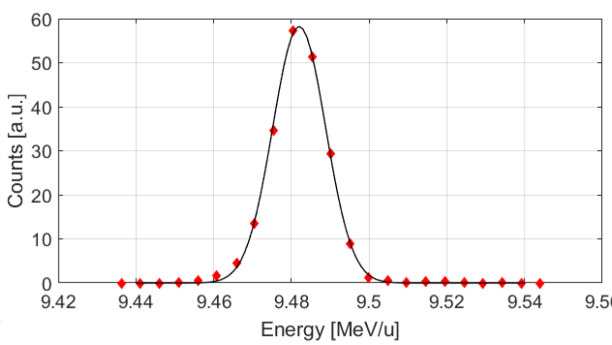


Figure 4: Results of the beam energy distribution measurement conducted at the end of the phasing process (data points in red, Gaussian fit in black).

## AUTOMATION AND APPLICATIONS

Starting from a setup with a 2.8 MeV/u beam from the normal conducting linac transported to DB4 through the super conducting linac with all cavities off, the phasing procedure can be summarized in the following steps:

1. Turn on the cavity to be phased at the maximum available gradient to increase the resolution of the measurement
2. Perform a rough phase scan at steps of 5 degrees to identify the region of the phases of interest
3. Perform fine scans around the two peaks and identify the zero-crossing phases
4. Identify the bunching zero-crossing. Set the phase at +70 degrees respect to one of the zero-crossings, scale the solenoids and the rest of the transport elements after the cavity to the new theoretical beam energy and verify that the beam reaches the FC in DB4. If the beam is not visible, the selected zero-crossing was the debunching one
5. Measure the transverse beam profile in DB4 and adjust the dipole magnetic field to center the beam in order to compensate for any mismatch between the expected and actual beam energies
6. Remove slit and check transmission. If necessary adjust correctors to compensate for any transverse kick that the cavity might have introduced and recover the beam transmission
7. Save and document the set-up of the machine and repeat the process to phase the next cavity

The procedure concludes with a precise measurement of the beam energy and energy spread. LabVIEW® and JAVA applications have been developed to partially automate several of the steps in the procedure [4]. In particular, software applications are used to complete the rough and fine phase scans, to measure the beam energy and to scale and document the set up of the machine.

## FUTURE DEVELOPMENTS

A new Python application will be developed to improve the phasing procedure using a general "Automatic Measurements Framework". It will be used to program a sequence of actions and measurements that could be predefined and launched. The main idea is to automate all the points described in the previous section. Particular attention will be given to the scans described in point 2) and 3) of that paragraph. The rough scan will include a peak detection algorithm capable to identify the two peaks after few scan iterations. The fine scans, performed around the peaks previously found, will have an automatic Gaussian fit routine implemented, which will help the users to identify the zero-crossings. The intermediate settings of the machine will be stored automatically. Measurement of beam energy could be automatically performed after each cavity phase tuning. The application will be using Python numeric and scientific libraries and automatic optimization algorithms already implemented at ISOLDE for beam optimization.

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